AALTO UNIVERSITY

School of Engineering

Degree Programme in Structural Engineering and Building Technology

Alexei Kesonen

Mechanical properties of Finnish rocks based on uniaxial compressive strength and tensile strength tests

Master´s thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology in the Degree Programme in Engineering.

In Espoo 25.5.2015
Supervisor: Professor Mikael Rinne
Instructor: D.Sc (Tech.) Juha Antikainen

Aalto-yliopisto Insinööritieteiden korkeakoulu

Aalto-yliopisto, PL 12100, 00076 AALTO
www.aalto.fi

Diplomityön tiivistelmä

Tekijä Alexei Kesonen		
Työn nimi Tavallisimpien suomalaisten kivilajien kalliomekaaniset ominaisuudet yksiaksiaalisten puristusmurtolujuus- ja vetomurtolujuuskokeiden perusteella		
Koulutusohjelma Rakenne- ja rakennustuotantotekniikan koulutusohjelma		
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Tiivistelmä

Yksiaksiaalinen puristusmurtolujuuskoe ja Brasilian vetomurtolujuuskoe ovat yleisiä laboratoriossa käytettyjä kokeita kalliomekaniikassa. Yksiaksiaalisella puristusmurtolujuuskokeella mitataan kivinäytteiden puristuslujuutta ja muodonmuutosominaisuutta. Brasilian kokeen avulla mitataan epäsuorasti kallionäytteiden vetomurtolujuutta. Tässä diplomityössä analysoitiin perusteellisesti yksiaksiaalisen puristusmurtolujuus- ja Brasilian vetomurtolujuuskokeiden tuloksia, jotka on saatu Aalto-yliopiston kalliomekaniikan laboratoriossa. Koska näytteiden valmistaminen laboratoriokokeisiin on aikaa vievää ja kallista, diplomityössä käsiteltiin merkittäviä kokeisiin vaikuttavia tekijöitä. Työssä kuvattiin myös kalliomateriaalien murtumismekanismit ja ominaisuudet.

Tuloksien analysointi suoritettiin käyttämällä tilastollista analyysia. Diplomityössä tutkittiin, miten eri kivilajien lujuus- ja muodonmuutosarvot vaihtelevat näytteiden syntyperän mukaan. Lineaarisen regressioanalyysin perusteella mitattiin, miten lujuuskokeiden tulokset ja muodonmuutosominaisuuksien arvot pystyvät tilastollisesti ennustamaan toisiaan. Kivilajien lujuusarvoja ja muodonmuutosominaisuuksien parametreja verrattiin muiden tutkimuksien saamiin arvoihin.

Työssä todettiin samojen kivilajien näytteiden yksiaksiaalisen puristusmurtolujuden olevan hyvin vaihteleva. Tutkimuksen tuloksena havaittiin, että yksiaksiaalisen puristusmurtolujuuden arvot ja Brasilian vetomurtolujuuskokeiden tulokset korreloivat riittävän voimakkaasti keskenään. Työn tulokseksi johdettiin muutama usean selittäjän lineaarinen regressiomalli yksiaksiaalisen puristusmurtolujuuden ennustamisesta Brasilian vetomurtolujuuskokeiden sekä muodonmuutosominaisuuksien tuloksista.

Avainsanat Yksiaksiaalinen puristusmurtolujuuskoe, Brasilian vetomurtolujuuskoe, Suomalaiset kivet, tilastollinen analyysi, Korrelaatio, usean selittäjän lineaarinen regressiomalli, Kalliomekaniikka

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Insinööritieteiden korkeakoulu

Aalto-yliopisto, PL 12100, 00076 AALTO
www.aalto.fi

ABSTRACT OF THE MASTER'S THESIS

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Abstract

This Master's thesis analyzes the results of two basic rock mechanics laboratory tests: Uniaxial compressive strength test and Brazil tensile strength test. This study also explores the known factors affecting the measurements in the uniaxial compression test and Brazil test results.

Since statistics and correlations play a significant role in research, a big part of this Master's thesis is built around the descriptive statistics and regression analysis. Consequently, in this Master's thesis the tests results for different rocks are described in detail and rely quite sufficiently on the statistical and regressional analysis.

In its main part, this thesis anylizes the linear relationship between the obtained results for mechanical parameters of the Finnish rocks obtained by condicting the uniaxial compressive and Brazil tensile strength tests. The conclusions regarding the compressive and tensil strengths values for the most usual Finnish rocks are made using statistical analysis. After that, the results obtained in this Master's thesis are compared against the results available from similar publications.

The analysis of results confirms that the strength and mechanical properties of the Finnish rocks differ quite a lot depending on the place of occurrence. Based on the statistical analysis made in this thesis, have been lead out several multiple regression models for determination uniaxial compressive strength.

Keywords: Uniaxial compressive strength test, Brazil tensile strength test, Finnish rocks, statistical analysis, correlations, multiple regression models, rock mechanics

Acknowledgements

This Master's thesis makes the end of my long learning journey in Aalto University. This time has coincided with a challenging though very enjoyable period of my life, including my military service, starting my professional life, and most importantly starting up my family. By the end of this journey I can say that I have learned a lot and I am leaving my Alma Mater with gratitude for equipping me well for my professional life.

First of all, I would like to thank my instructor Dr Juha Antikainen for his invaluable help and support in my studies, for his generous suggestions and a live example of a good scientist.

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Alexei Kesonen
Espoo 20.4.2015

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INTRODUCTION

1.1 Background of this thesis

Uniaxial compressive strength of the rock is one of the most popular tests and values in rock mechanics. It is one of the basic parameters for rock classifications and design. Since uniaxial compressive strength makes such an important characteristic of the rock and the Laboratory of Rock mechanics of Aalto University School of Engineering has a large amount of data on various rock material strength, this thesis has decided to focuse on the analysis of this interesting and sufficient data.

1.2 Main goals of this master thesis and learning objectives

The main goal of all laboratory tests is to understand and describe the prodigies of nature. The study of mechanical properties of rocks opens the way to the interiors and wealth of the Earth. In addition to studying the stones, rock mechanics is another way to check human stamina. Extraction of natural resources, tunnels connecting cities and countries would have been impossible to build without persistence, dedication and knowledge of rock properties accumulated from rock mechanics and research work in laboratories.

The first interim goal of this thesis is to analyze the results of a large amount of the uniaxial compressive strength tests and Brazil tensile strength tests which were made in the Laboratory of Rock mechanics of Aalto University School of Engineering. It is a well known fact that the results of strength tests conducted on small rock specimens may not always accurately fit the larger rock masses which will be used for engineering purposes.

The second interim goal of this thesis is to understand the hardships and nuances of conducting the uniaxial compressive strength tests and tensile strength tests.

Based on this two interim goals, this thesis makes an attempt to determine a possible linear dependence between the mechanical properties of the tested rocks samples, and identify the factors that significantly impact on strength properties of different rocks, and finally, compare the obtained results with other similar researches.

The findings of this thesis could be useful in designing and modelling of the underground constructions. Such an analysis could also be interesting from a scientific point of view as it could be useful in future research as prediction of values and mathematical modelling.

1.3 Restrictions of this thesis

To produce reliable predictions, rock mechnics requires to make conclusions based a large amount of collected data, gathered at different time intervals and clearly classification by groups. However, if for some rocks there are plenty of tests made and a large number of results is available, for others the test and results are just a few. Therefore, this thesis compares only that part of the main Finnish rocks on which enough data is available at the Laboratory of Rock mechanics of Aalto. This selection of data allows to produce convincing statistical analysis.

Additionally, this thesis limits the research of the uniaxial compressive strength of the rock to descriptive statistics, linear and multiple regression analyses.

2 PROPERTIES OF ROCK

2.1 History

Rock as material is probably the oldest substance on the planet, and over its history it undergoes various physical and mechanical stresses. Once upon a time, at the birth of the Earth, melted rock at the upper layers became hard and formed the Earth's crust – the lithosphere. Located underneath the asthenosphere, it is highly viscous and it slowly flows all the time. Under the influence of this motion, the upper hard plate was cracked to tectonic plates. /1/ As a concequence of all this experiences and loadings, the rock masses have already been stressed – as in situ pre-existing state of stress.

Thus, it is the geological factors that influence mechanical properties of rock masses. Rock masses are divided by discontinuities and fractures, which are different in shape and sizes. As such, rock masses consist of small and large rock blocks that reside under the influence of external loads. These discontinuities have many geometrical and mechanical features which often govern the total behavior of the rock mass. Failing is often associated directly with the discontinuities. Fractures can be formed by pulling apart and by shearing. The overall geometrical configuration of the discontinuities in the rock mass is called the rock structure. /2/

Rock is known to have different properties in different directions. While excavating a tunnel, the pre-existing stress is redistributed by the engineering activities, and this result in the increase of stress in one place and decrease in another. Vertical stress component is caused by the weight of the overlying strata, whereas the high horizontal stress is mainly caused by tectonic forces. /2/

2.2 Geology

Mechanical properties of rocks are affected by the strength of the rock which depends on mineralogical composition and its structure. Mineralogical structure of the rocks depends on the quality of minerals, weathering characteristics, consistency of minerals, its size and shape. External factors which are also important for strength inlcude: temperature, humidity, loading speed. Therefore, it is often said that mineralogical properties of the rocks depend on their origin. /3, 4/

By their origin, all rock can be separated into three groups: igneous, sedimentary and metamorphic. Igneous rocks form when the magma solidifies and crystallizes. Sedimentary rocks represent the hardened formations of sand, clay and organic materials. Finally, metamorphic rocks are formed by different temperature and pressure from other rock types.

Since rocks are composed of minerals, the presence of certain mineral composition and their origin divide the rocks into certain groups. Usually there are 3–5 minerals composed in each rock, out of more than 4000 minerals counted this day. Minerals are formed by geological processes and are divided to 7 groups by their crystal structure. The properties of minerals which serve to distinguish them are density, gloss, magnetism, radioactivity, color and optic properties, mechanical properties, specific gravity and others. The size of one particular mineral grain in rock is about 0.1– 1 mm. /5/

1) For the engineering purposes, rocks can be divided into four groups:
2) nonoriented strong rocks (Diabase, diorite, granite, pegmatite, granodiorite)
3) orientated strong rocks (Hornblende gneiss, mica schist, amphibolite, mica gneiss, phyllite)
4) strong rocks with migmatic structure (Veined gneiss, coarse pegmatite, weakly assimilated migmatite)
5) loose and weathered rocks (Shale). /4/

More than 50% of the Finnish rocks are nonorientated or slightly orientated igneous rocks, and their mineralogical properties and grain size affect the strength properties of these rocks. Strength of the rock means the maximum capacity of material to resist influenced loads. Strength properties of the minerals basically depend on the properties of its ions as mass, charge, size and atomic structure. The smaller mineral grains is, the larger is the cohesion between its surfaces, and the stronger is the rock. Additionally, roughness of the grains also has a positive effect on the strength of the rock. Roundish grains in rocks relate to the strength properties of the minerals that keep these grains together. Presence of strong minerals such as Pyroxenes, Amphiboles and Quartz also impacts on the strength properties of the rocks. /4/

Strength of the rocks is also known to depend on the order of mineral crystallization. Minerals that crystallize first form the main structure, and the minerals that crystallize latest fill the empty spaces. Therefore, rocks consisting of fibrous and splintery minerals are usually stronger; while fine-grained and glassy rocks are usually stronger than the rough and coarse grain rocks. /4/

Strength properties of orientated rocks depend, besides of all above mentioned factors, also on the orientation of elongated and platy grains. Usually the stronger is the level of schistose, the lower the strength properties of the rock material are. /4/

Finally, the group of rocks with mixed structure may include nonorientated and orientated rocks. Strength properties of rocks with mixed structure depend on the the strength of the rocks ingressed into it and the substance that bends it together. /4/

2.3 Access to the rock

With the advent of diamond drill bits, the study of rock masses took a giant step forward. The product of borehole drilling is a core material. According to the obtained core materials, it is possible to make conclusions about the quality of rock mass, its types and fractures. The obtained core material could be used for measuring mechanical properties of intact rock. /2,6/

3 DEFORMATION AND STRENGTH

When working with natural materials such as rock, it is important to know and understand its properties and behavior at the loading processes. For the concrete structures, the peak strength is the final limit of design possibilities, whereas for engineering in rocks is it important to know that the rock structure will pass into the post-peak region. That is why it is so important to know behavior of the rocks after their peak strength has been reached. /2/

3.1 Stress and strain

Stress can be expressed as the applied force per unit of area - *pressure*. Usually all failures can be qualified as certain stress quantities. Materials can be stressed at the same time by different types of stress. Stress can be expressed as:

$$\sigma = \frac{F}{A} = \frac{[kN]}{[m^2]} \tag{1}$$

Stress is a tensor quantity, which means that it has magnitude, direction and “the plane under consideration” /2/

Under the influence of the forces, materials tend to deform. At the compression, the axial length reduces while the diameter expands. At the same time, materials tend to elongate at tension, while at same time its diameter tends to contract. This phenomenon is called Poisson effect and can be defined as Poisson’s ratio, /2/ ,

$$v = \frac{\varepsilon_l}{\varepsilon_a} = \frac{lateral\ strain}{axial\ strain} \tag{2}$$

Correspondingly, the axial strain is a ratio of change in length to initial length and can be defined as:

$$\varepsilon_a = \frac{\Delta l}{l_0} = \frac{change\ in\ measured\ axial\ length}{original\ measured\ axial\ length} \tag{3}$$

while the lateral strain comes from:

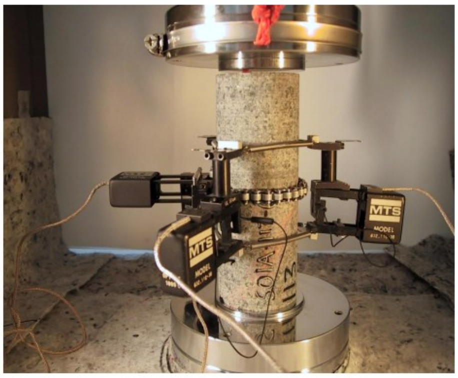
$$\varepsilon_l = \frac{\Delta d}{d_0} = \frac{change\ in\ diameter}{original\ undeformed\ diameter} \tag{4}$$

Assuming that rock is an elastic material, the parameter of elastic modulus or Young's modulus can be defined as:

$$Young's\ modulus, E = \frac{\sigma_a}{\varepsilon_a} = \frac{axial\ stress}{axial\ strain} \tag{5}$$

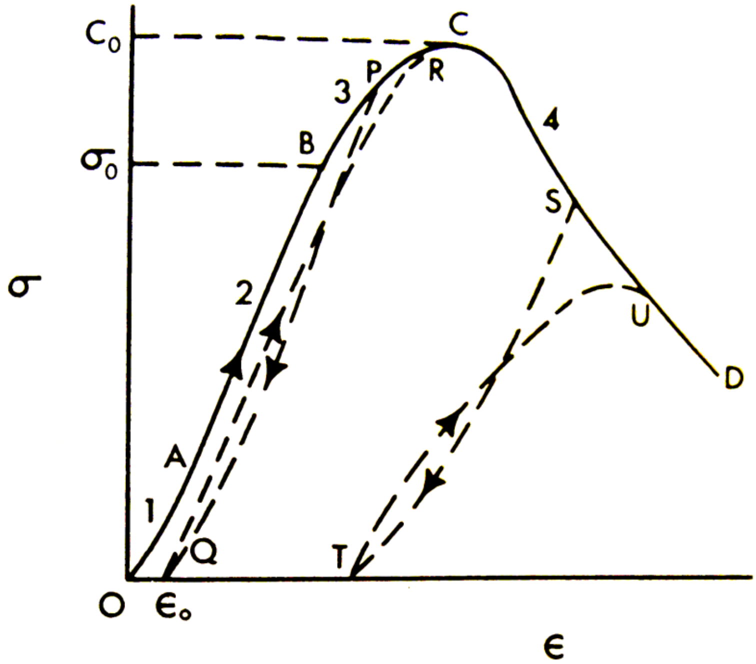
3.2 Uniaxial compression test and the stress-strain curve

Uniaxial compression is the simplest form of loading. Uniaxial compression is measured by loading the right circular cylinders along its axis. The height to diameter ratio of the sample should be 2.5–3 and the diameter should be approximately 54 mm. The uniaxial compressive strength comes from the ratio of the maximum load carried by a specimen divided by original cross-sectional area. During the measurement of compression by means of strain gauges, the deformability is measured as well. The result of the measurement is usually depicted graphically by a stress-strain curve. By analyzing the stress-strain curve, it is possible to obtain the parameter of Young's modulus and measure deformability. Strain gauges measure the axial and circumferential strains at the loading process. /2/



Picture 1. Uniaxial compressive stress test (Photo by Pekka Eloranta, Aalto)

The stress-strain curve can be divided into several parts by its form. At the beginning of loading, the closing of microcracks occurs inside the specimen, which is shown in part O–A in Picture 2,



Picture 2. Complete stress-strain curve /8/

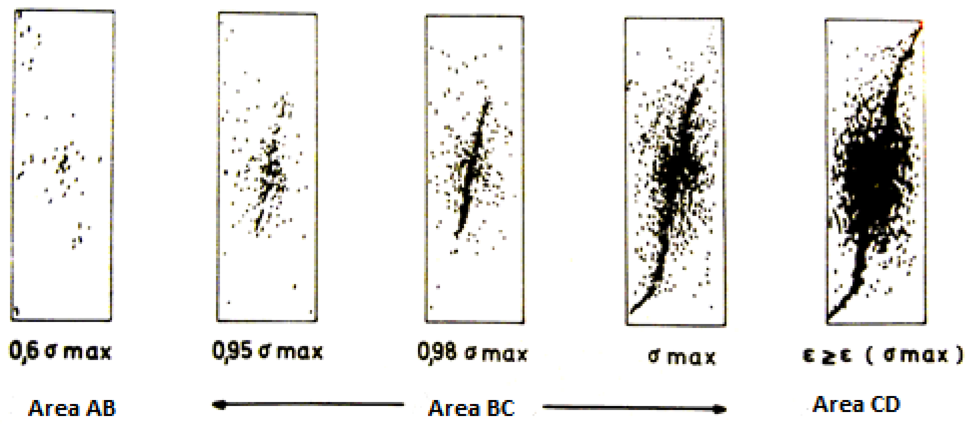
that is one of the reasons why curve looks concave and the second depends on the flatness of the specimens ends. Nevertheless, at the first two parts of the stress-strain curve, behavior of the rock sample is near the elastic, which correponds to parts O–A and A–B in Picture 2. This means that if loading was stopped at this two parts of the curve, the specimen will not receive permanent deformation. /2,8/

On the B-C part of the stress-strain curve shown in Picture 2, permanent deformations start to occur at the cracking damage value σ_0. Therefore, the stress-strain curve starts to take more horizontal direction. If loading were ever hold at the constant value, at the B-C part of the curve microcracks would still occur; and if the loading were stopped in this part of the curve, the specimen will receive permanent deformation, as it shown in part P-Q in Picture 2. /8/

Maximum load carried by the the specimen is achieved at point C in Picture 2, which is also called the peak stress or the uniaxial compressive strength σ_c. Point C divides the stress-strain curve drawing into two parts pre peak in part O–C and post peak in part C–D. /8/

The fourth part of the curve can be determined by the kind of material that is dealt with: ductile (region B–C) or brittle (region C–D). On ductile material, strain will grow at the same stress level; while with brittle material stress and strain will drop to zero /2,8/

At the compression loading, inside the sample two compression zones are formed unequal by values and perpendicular to each other. Along these zones, fracture of the the specimen happens at the action of shear stress. At the uniaxial compression, microcracks continually increase from the beginning of the part B–C, as can be seen from Pictures 2 and 3. The direction of formed microcracks is same as the direction of maximum shear stress, as can be seen from Picture 3. Until it breaks into pieces at C–D part of the curve. /7,8/



Picture 3. Development of microcracks at uniaxial compressive stress /7/

3.2.1 Failure mechanism of specimens in compression

Failure mechanism was explored by Paul and Gangal (1966) who concluded that rock masses are not uniform and contain randomly orientated cracks of various size.

Orientation of the cracks with respect to the applied stress has impact on the grown of the cracks. Under the influence of the applied uniaxial compression, the cracks begin to grow and branch until the cracks become oriented in direction of the applied stress. Firstly, the cracks with most favorable orientation will grow and then all the rest will increase with stress. Failure occurs due to the amount of densely appeared cracks and therefore the specimen lost its ability to sustain loadings. /9/

3.3 Indirect tensile strength

Tensile strength of the rock is the maximum stress that rock can sustain under the influence of tensile force. Measuring of tensile strength by a direct test is difficult due to a hard specimen's preparation process and also due to difficulties with gripping. Therefore, tensile strength is usually measured by the indirect test in which tensile stress is generated by compressive loading. The tensile strength of rock material is much lower than the compressive strength. In Brazil test, the tensile strength is measured by diametral compression. Calculations of the test are based on the elasticity theory assuming that material are homogeneous, isotropic and linearly elastic. /9/

3.3.1 Brazil test

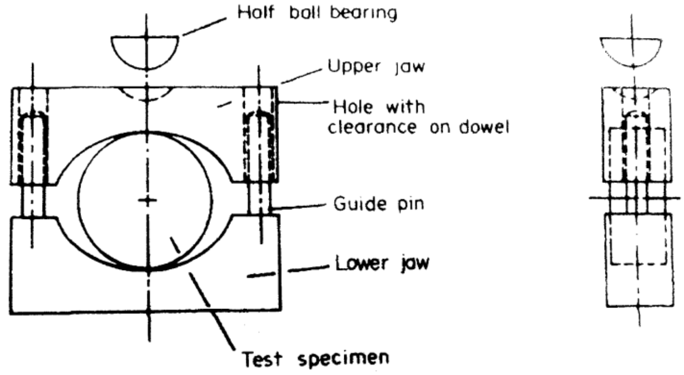
In Brazil test, a cylindrical sample is compressed along its length between two loading jaws. This test arrangement is illustrated in Picture 4. The specimen length's ratio to the raduis should be 0.9–1.1. Tensile stress at failure, σ_t is calculated from the failure load as function of the compressive force and the specimen dimensions:

$$\sigma_t = \frac{2P}{\pi D t} \tag{6}$$

Where P is load on the specimen,

D is the diameter of the specimen,

t is the thickness of the specimen.



Picture 4 Apparatus for Brazil test /10/

On average, the uniaxial compressive strength makes 20–25 times point load strength $I_{s(50)}$ and is approximately 0.8 times the uniaxial tensile strength or Brazilian tensile strength (ISRM, 1972). /10,2/

According to Vutukuri *et al* (1974), Brazilian test can be valid only if vertical crack formation starts from the center of the specimen and spreads along the load axis. /9/

Specimen geometry according to the findings of Bernenbaum and Brodie (1959b) as well as Yu (1963) reveals that if the ratio between the thickness of the disc and the diameter increases, the tensile strength decreases. /9/

According to Lundborg (1967), tensile strength of tested granites cylinders tend to decrease with increase of volume of specimens. Additionally, Bernaix (1969) reported that tensile strength of tested marquise limestone decreases with the increase in specimen diameter. Mellor and Hawkes (1971) reported that with the increase in disc thickness, tensile strength value tend to decrease. Mellor and Hawkes (1971) also reported that the increase in loading rate increases the strength. According to Dube and Singh (1972), humidity tends to decrease tensile strength. /9/

4 FACTORS AFFECTING THE MEASUREMENT

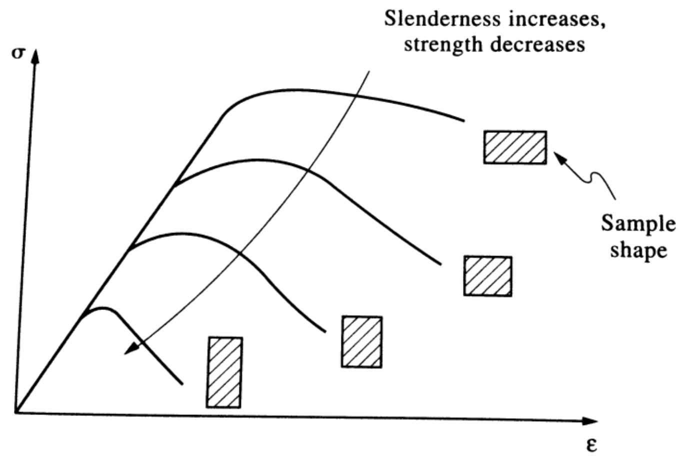
To obtain reliable test results, several things need to be understood and taken into account while measuring. The impact of such things as the specimen's size, shape, loading conditions, test equipment, and environmental make a significant effect on successful results of the measurements.

4.1 End effect

End effect means the difference between elastic properties of steel platens of testing equipment and rock specimen, that affect on the test results. Moreover, the difference between coefficients of friction of platens and specimen also has its own effect on the test measurement. Due to it, the growth of cracks near platens restrains, and then the specimen deformation is not uniform. Therefore, the best test result can be achieved while using the platens of the same diameter as the rock specimen. Hence, distribution of the stress in the specimen is dependent on its geometry. /6,9/

4.2 Shape effect

It was observed experimentally that the shape of the specimen has no influence on the elastic modulus. Strength increases with the growth of the ratio of diameter to length. As a result, slender shaped specimens sustain less loads than the squat shaped ones in uniaxial compression. /2/

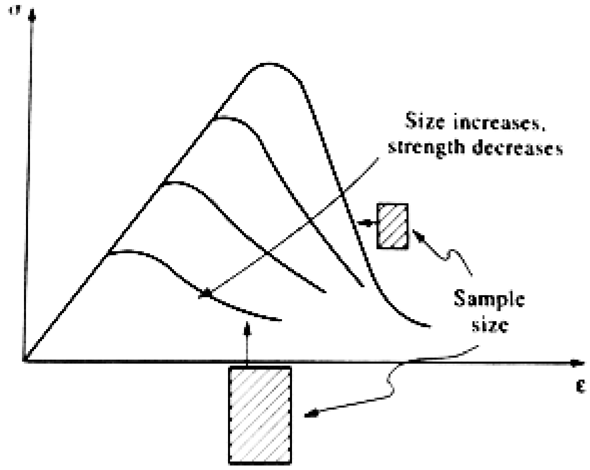


Picture 5. The shape effect in uniaxial complete stress-strain curve. /2/

4.3 Size effect

It has been noted from the experimental measurements that the larger the tested sample is, the lower is its compressive strength and brittleness. The reason for this is most likely the bigger quantity of microcracks in larger samples and the larger probability to fail resulting from it. The sample size does not impact on the elastic modulus. Picture 6 represents the size effect in the stress-strain curve. /2/

According to Vutukuri *et al*. (1974), the specimens with the height to diameter ratio in range from 2.5 to 3.0 are elastically stable and stress distribution in specimens is thus more uniform. /9/



Picture 6. The size effect in uniaxial complete stress-strain curve. /2/

Brady *et al*. (2004) reported, however, that existence of size effect has not gained universal acceptance. /6/

4.4 Loading rate

The loading rate for uniaxial compression test, as recommended by ISRM (International Society for Rock Mechanics), used to be 0.5–1.0 $\frac{MPa}{s}$. According to Brady *et al*. (2004) and referring to ISRM commission (1979), while testing rock samples for uniaxial compression it is correct to use axial strain as a controlling variable, and the recommended strain rates between $\frac{10^{-5}-10^{-4}}{s}$. /6,10/

Significant impact on the results also have the very fast and very slow strain rates. According to Vutukuri *et al*. (1974), the compressive strength of rock usually increases with the increase in the rate of loading of specimens. /9/

4.5 Environmental effects

Enviromental effects need to be taken into account; among them the most significant are moisture. According to Vutukuri *et al*. (1974), moisture may cause significant reduction of compressive strength of rocks. Due to the moisture content difference in strength can be several times lower in comparison to dry samples. /9/

That is why for obtaining optimal results, and due to the fact that moisture content changes along the specimen preparation process, the ISRM committee recommend to store the prepared specimen no longer than for 30 days, under conditions conductive to the preservation of natural water content. /10/

4.6 Anisotropy and inhomogeneity

Elasticity as the property of ideal material is taken for a basis for evaluation of the rock material quality properties. Basic properties required to describe elasticity include isotropy, homogeneity and continuity.

It has been assumed for modelling of underground facilities that mechanical properties of rock material is isotropy. Isotropy means equal properties in all directions and opposite to it is anisotropy. In fact, many rocks have anisotropic properties due their different crystal orientation (bedding and cleavage planes). Strength quality of rock materials depends on rock structure and on direction of applied force; therefore, rock materials react differently to forces in different directions. During the measurement of compressive strength, it is important to take into account the direction of the applied force with respect to the rock structure. Dependence of compressive strength to the angle of discontinuities has been studied by several authors such as Brady and Brown (1985) and Jaeger (1972). According to theory, each plane can sustain defined quantity of shear stress, slip along wakness occurs when shear stress is become equal to shear strength. Obtained distribution of the results show that minimum values of compressive strength revealed at a cleavage angle between 30–40 degrees relative to the direction of principal stress. /2,6,11/

Homogeneity is a measure of the physical continuity of a body. Homogeneous material has the same properties at every point. Homogeneity of rock is dependent on scale; opposite to it is inhomogeneity. Rock material is inhomogeneous as it consist of various mineral grains. /2/

Summing up, rock is not a continuum due to the amount of joints, cracks and pore spaces. From the above described, it can be concluded that rock material is linearly elastic only in exceptional cases.

According to Farmer (1968), most elastic rocks are fine-grained, massive and compact extrusive rocks, hypabyssal igneous rocks and some fine-grained metamorphic rocks. Less elastic are coarser-grained igneous rocks and fine-grained compacted sediments quasi-elastic rocks. /11/

5 DESCRIPTIVE STATISTICS

For conducting statistical analysis, this thesis will follow the approach suggested by Freedman, Pisani and Purves (1998). /12/

5.1 Histogram, average and standard deviation

The basic concepts used to summarize list of numbers are average (arithmetic mean), standard deviation and histogram. The first analysis of statistical data is typically expressed by a histogram. Histogram is a graphical representation of the distribution in which the areas of the blocks represent percentages. The horizontal axis represents distribution intervals, and the vertical axis represents the percentage of each interval to all data. Area of the histogram is equal to 100 percent. Through a histogram it is simple to create the general Picture of the data's center and spread properties. Histogram is symmetrical while its area is divided into half about the average. /12/

The average value of the list of numbers means the sum of all the values of the list divided by quantity of numbers in the list. Difference between the values of the list and the average of the list is expressed by a standard deviation. Standard deviation (SD) shows how many numbers spread around the average of the list. /12/

5.2 Normal curve and normal aproximation

A normal curve resembles an ideal histogram; it is symmetric about 0, with the total area under the curve equaling 100 %. The horizontal axis is represented by standard units and the vertical axis is represented in percentage per standard units. Standard units show how many standard deviation values differs from the average. The average in standard units is equal to zero; the values that are less than the average get a minus sign, and values that are bigger than the average get a plus. The area under the normal curve between -1 and 1 is about 68%, and between -2 and 2 is about 95%. If the list of number follows the normal curve, than by replacing its histogram by the normal curve it is possible to do a normal approximation and estimate the percentage of values by finding the area under the normal curve. Equation of the normal curve can be expressed as:

$$y = \frac{100\%}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \tag{7}$$

where e is matematical constant known as Napier’s constant. /12/

By repeating the same measurements again, the obtained result may differ due to a chance error. Some values from the list data could considerably differ from the average, and these values are called outliers. Outliers are known to significantly affect the overall picture of the statistical data. /12/

6 CORRELATION AND REGRESSION

In statistical analysis, a strong association between two variables helps to predict one from the other. The horizontal axes x usually represents an independent variable and the vertical axes y shows the dependent one. The results can be shown in a scatter diagram which represents a cloud of points. By measuring the average of independent variables and the average of the dependent ones, it is possible to identify the center of this cloud. The spreads are represented by a standard deviation of x and y axes. If the data is tightly clustered around a line, there will be a strong linear association between two variables. Correlation coefficient *r* reports strength of the correlation between parameters. This correlation can be positive or negative, depending on the analyzed values of the data. While correlation coefficient is equal to 0, the cloud is formless. The maximum correlation value is equal to 1 or -1 and it is named a perfect positive or negative correlation. To compute the correlation coefficient of two list of numbers, each variable needs to be converted to standard units. Then pairs of numbers in standard units must be multiplied and average of the products gives a correlation coefficient. /12/

6.1 Simple linear regression

Regression method predicts the value of one from another using a linear association. Having a value of x in standard units, it is possible to predict the average value of y in standard units. Freedman *et al*. (1998) explains it as change on one SD on x, cause change equal to only r SDs on y, on the average. This regression estimates presented graphically gives regression line for y on x. */12/*

The regression line can be represented as:

$$y = mx + b \tag{8}$$

Where *m* is the slope of the regression line which can be defined as:

$$\frac{r \times SD\ of\ y}{SD\ of\ x} \tag{9}$$

b is the intercept of the line; it is predicted value of y when x is equal to 0.

Relationship of one data list to another are usually figured on a scatter diagram. The regression method predicts values, but presence of errors is possible. Errors are shown as distances from the actual values to the regression line.

6.2 Multiple regression

A multiple regression model checks correlations of two or more explanatory or independent variables to the predicted dependent variable. An example of equation of the multiple regression model is showed below:

$$Y = X\beta + \epsilon \tag{10}$$

where Y is dependent variable, the one that is modeled,

X is an $n \times p$ design matrix of independent variables,

β is a $p \times 1$ vector of parameters,

ϵ is an $n \times 1$ random vector that is generally not observed.

Difference from the linear regression is that in multiple regression there are several explanatory variables with their own slope coefficient. /13/

6.3 Coefficient of determination and analysis of variances

High value of coefficient of determination or R-squared indicates that data explains well statistical model; and vice versa low R-squared indicates scanty fit. R-squared can be defined as the relation of explained variation to the total variation. In this case, the regression line shows ideal predictions, but the actual values can vary from the fitted line by the error. Variability can be explained by the analysis of variance:

$$SST = SSM + SSE \tag{11}$$

where:

SST is total sum of squares (Sum of the squared differences between dependent variable and its average value), *SSM* is model sum of squares of the deviations of the predicted values from the mean value of dependent values,

SSE is residual or error sum of the squares distances/errors between dependent values and regression line.

Than R-squared can be presented as the model sum of squares to the total sum of squares:

$$R^2 = 1 - \frac{SSE}{SST} = \frac{SSM}{SST} \tag{12}$$

More theoretical explanations will be briefly added along with the analysis of the data. /13,14,15/

7 TEST DATA AND METHODS OF ANALYSIS

7.1 Description of data

In the Laboratory of Rock mechanics of Aalto University School of Engineering, a mighty work of "crushing" rock samples has been accomplished. In the period of 1994-2014, there were more than 1500 specimens tested to study mechanical properties of different rock samples from all over Finland. These tests also measured the uniaxial compressive strength, and tensile strength of rock by Brazil test. The data were obtained from more than 100 different rocks. During the tests, the data on density of the samples, Young's modulus and Poisson's ratio were also collected. Additionally, the grain size of samples was described to some degree as the average grain size of the sample or by the interval. Occasionally, the schistosity, cracks and cavities and also irregular failures and errors in measurements were also registered.

7.2 Research plan and methods of analysis

For the complete analysis of this large amount of data, the plan for research was defined. The research plan aimes to establish the clear boundaries and segregation of properties that are necessary and possible to check and to compare. For obtaining these results, a list of actions was generated similar for all rocks, which is presented below.

Since the whole data were presented in a big MS Office Excel document, for further analysis it was necessary to separate the available data by rock groups. In fact, the data consist of the results of only two tests, Uniaxial compressive strength test ant Brazil test. Additionally, from the scientific point of view, it was meaningful to compare and to analyze mechanical properties of the rock samples collected from different regions of Finland; therefore, some other groupings were also done. The organizations of the data is shown in the list below:

1. Separation of the test data by rock groups
    a. General statistical information about the rock
        i. Relations of mechanical properties
            1. Descriptive statistics

2. Simple linear regression
3. Multiple regression analysis

ii. Analysis of the strength properties of the samples by different grain size (variation properties, relationships)

iii. Analysis of the strength properties by relating comments.

2. Separation by place of occurrence
   a. Descriptive statistics of the strength properties of different rock samples (minimum and maximum values, average, standard deviation) Collection of the data to Table by place of occurrence.

Additional properties to check:

- Comparison of obtained data of strength properties with another similar researches.

8 ANALYSIS OF THE DATA BY ROCKS

All statistical calculations was constructed on the *IBM SPSS Statistics 22* program. Each rock was analysed separately. Statistics of granites will be shown in more details with equations, pictures and tables. In further chapters, most part of pictures and tables will be moved to the appendicies of the thesis, numbered in order of appearence.

8.1 Granites

Analysis starts with examination of the granites. In total, 139 granite rock samples have been tested for uniaxial compression. Of these, only 109 samples were also tested for tension strength using Brazil test. Rock samples were collected from 28 different regions of Finland and one part of 8 samples originated from Austria. 13 sets of rock samples were collected from Espoo, and a possible reason to this was the large-scale construction of Western metro at the moment of data collectiton.

8.1.1 Descriptive statistics

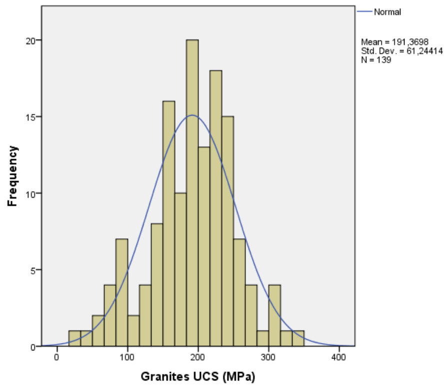
Descriptive statistics of all granite samples are presented in Table 1.

Table 1: Descriptive Statistics Granites

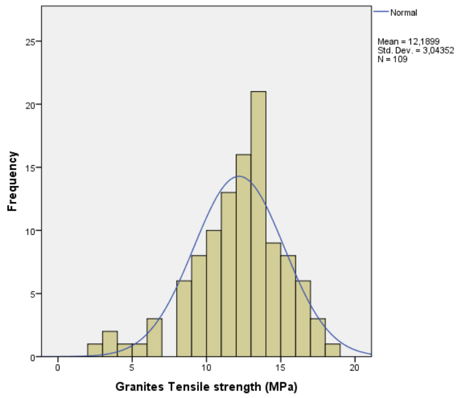
	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	139	**26,60**	345,9	**191,4**	5,2	**61,2**
Tensile strength (MPa)	109	**2,57**	18,3	**12,2**	0,29	**3,0**
Young’s modulus (GPa)	140	11,2	82,8	69,1	1,02	12,2
Poisson’s ratio	140	0,00	0,30	0,23	0,0031	0,04
Density (kg/m3)	140	2363	2714	2620	3,8	45,3

As seen from Table 1, the standard deviation values are high, compared to the average values (table 1). The reason for this may be the different origins of the rock samples. It is also very important to keep in mind that mineralogical content, grain size, possible cracks and other properties might have considerable effect on the strength results.

Pictures 7 to 11 present the histograms of all obtained parameters.

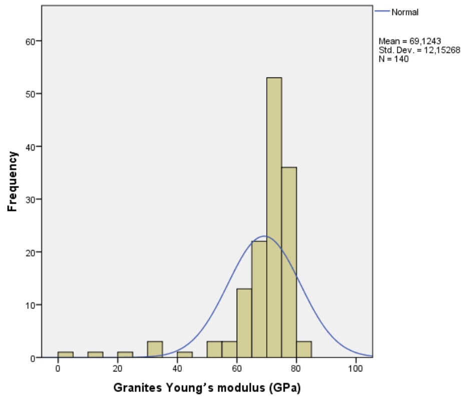


Picture 7. Histogram for the UCS of the granite rock samples

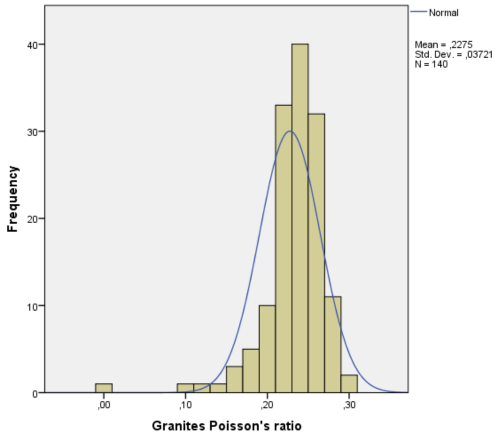


Picture 8. Histogram of Tensile strength of granites in total of 109 tests

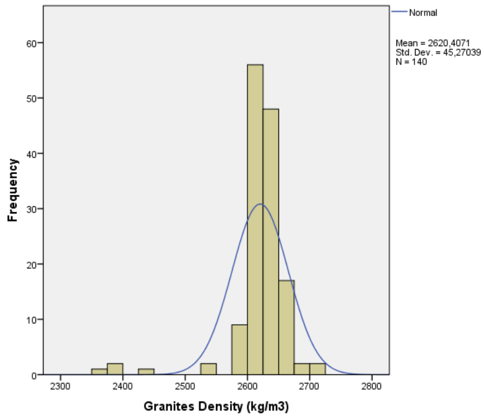
As can be seen from Pictures 7 and 8, distribution of the UCS and tensile strength for tested granites is quite near normal for 139 and 109 samples. It can be seen from Table 1 and from histograms in Pictures 7 and 8 that average value of uniaxial compressive strength of tested granites is more than 15 times greater than average value of tensile strength.



Picture 9. Histogram show the distribution of the Young's modulus values of granites



Picture 10: Histogram of Poisson's ratios of the granite samples



Picture 11. Distribution of densities of the granite rock samples

As can be seen from pictures 9 to 11, the distribution of Young's modulus (picture 9), Poisson's ratio (picture 10) and density (picture 11) not show the same symmetry as UCS and tensile strength.

8.1.2 Linear regression

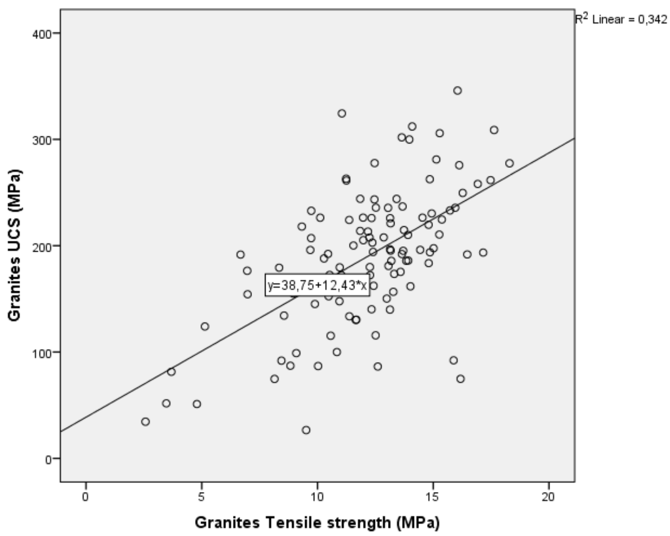
Results of the linear regression model of the UCS and tensile strength of the granites presented in Table 2.

Table 2: Correlations

		Granites Tensile strength (MPa)
Granites UCS (MPa)	Pearson Correlation	**0,585****
	Sig. (2-tailed)	0,000
	N	109

**. Correlation is significant at the 0.01 level (2-tailed).

As can be seen from Table 2, there is a significant positive linear relationship between the UCS and the tensile strength of tested granite specimens, $r(107)=0.585, p=0.000$. Number 107 means the degrees of freedom that for Pearson correlation is equal to the total number of tested samples subtracted 2 $(109-2=107)$. The observed significance level p is the chance of getting a test statistic as extreme as, or more extreme than, the observed one. Picture 12 shows scatter plot of tensile strength to uniaxial compressive strength.



Picture 12. Scatter plot of tensile strength to UCS

As can be seen from the scatter plot in Picture 12, there is a positive association between the uniaxial compressive strength and the tensile strength of tested granite rock samples.

The dependent variable in the model is UCS placed on axis *y*, as can be seen from Picture 12; and the independent variable is tensile strength placed on axis *x* of Picture 12.

If assumed that between UCS and Tensile strength there is a linear statistical dependence, then the equation of the model can be defined as:

$$UCS = \beta_0 + \beta_1 TensileStength + \varepsilon \tag{13}$$

where β_0 is a constant and β_1 is a regression coefficient or a slope. Number of observations n is equal to 109.

The total degrees of freedom will be equal to $n - 1 = 109 - 1 = 108$, and the number of coefficients k is equal to 1, because only one independent variable was used – tensile strength. Residual degrees of freedom is equal to $(n - (k + 1)$ that is $109 - 2 = 107$.

Statistical significance of the model is tested by F-test for coefficient of determination. Null and alternative hypothesis are defined as:

H_0: β_1=0

$H_{A:}$ β_1 differs significantly from zero.

And value of F-test can be defined as:

$$F = (n - 2) \times \frac{R^2}{1 - R^2} \tag{14}$$

Statistical significance of the regression coefficient is usually checked by t-test. The coefficient of regression line will not be equal to zero if between UCS and tensile strength are linear relationship.

H_0: $\beta_1=0$

H_A: $\beta_1 \neq 0$

Degrees of freedom for the t-test is equal to:

$$DF = n - k - 1 = 109 - 1 - 1 = 107 \quad (15)$$

Table 3 presents summary information about the model.

Table 3:Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0,585[a]	**0,342**	0,336	52,7

a. Predictors: (Constant), Granites Tensile strength (MPa)

As can be seen from Table 3, R-squared value is equal to 0.342 and this means that the estimated model explains only 34.2 % of the variation of the dependent variable. Analysis of variances is shown in table 4.

Table 4:ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Model Regression	154553,8	1	154553,8	55,691	**0,000[b]**
	Residual	296947,3	107	2775,2		
	Total	451501,1	108			

a. Dependent Variable: Granites UCS (MPa)

b. Predictors: (Constant), Granites Tensile strength (MPa)

As analysis of variances shows in Table 4, and according to equation 11:

Total sum of squares is equal to $SST = 451501.1$

Model sum of squares is equal to $SSM = 154553.8$

Residual sum of squares is equal to $SSE = 296947.3$

than R-squared can be defined according to equation 12:

$$R^2 = 1 - \frac{SSE}{SST} = 1 - \frac{296947.3}{451501.1} = 0.34 \tag{16}$$

and residual mean square and model mean square as equatons 17 and 18:

$$Residual\ mean\ square\ = \frac{SSE}{n-2} = \frac{296947.3}{109-2} = 2775.2 \tag{17}$$

$$Model\ mean\ sqare = \frac{Model\ sum\ of\ squares}{Respective\ degrees\ of\ freedom} = \frac{154553.8}{1} = 154553.8 \tag{18}$$

and value of the F-test than:

$$F = \frac{Model\ mean\ square}{Residual\ mean\ square} = \frac{154553.8}{2775.2} = 55.69 \tag{19}$$

As can be seen from Table 4 and equations 13, 16–18, null hypothesis H_0 of the coefficient of determination test can be rejected with 0.000 significant level: β_1 differs significantly from zero. Obtained coefficients is shown on table 5.

Table 5: Coefficients[a]

Model		**Unstandardized Coefficients**		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	**38,752**	**20,921**		**1,852**	**0,067**
	Granites Tensile (MPa)	**12,429**	**1,666**	0,585	**7,463**	**0,000**

a. Dependent Variable: Granites UCS (MPa)

Equation of regression line can be defined from Table 5: column header- *un unstandardized coefficients* –B, column *Std.Error* shows the standard error values, colum *t* shows t-test values of coefficients, and column *Sig* shows the level of significance p-value.

Equation of regression line can be defined as:

$$UCS = 38{,}752 + 12{,}429 \times TensileStength \tag{20}$$

Regression coefficient is equal to $\beta_1 = 12.429$, and statistically significant with *p* value less than 0.05.

Coefficient of constant β_0 is equal to 38.752 and it is not statistically significant at 0.05 level of significance, but *p* is very close equal to 0.067. T-test for intercept parameter β_0 is not reasonable.

T-test value of regression coefficient for the β_1 can be measured as:

$$t = \frac{\beta_1}{Std.Error} = \frac{12.429}{1.666} = 7.46 \tag{21}$$

t-value for the β_0 is equal to:

$$t = \frac{\beta_0}{Std.Error} = \frac{38.752}{20.921} = 1.852 \tag{22}$$

For the linear regression with one independent value, t-test and F-test for the null hypothesis are equivalent:

$$\sqrt{F} = t \rightarrow \sqrt{55.691} = 7.463 \tag{23}$$

and that means that for linear regression analysis on of the tests (F-test or t-test) will be sufficent.

8.1.3 Multiple linear regression

For the construction of a possible multiple regression model, it is necessary to check parameters for correlations. Table 6 presents the results of linear correlations of all obtained parameters to each other. Significant correlations in table 6 are marked bold. As can be seen from Table 6, there are positive significant correlations between UCS and tensile strength, UCS and Young’s modulus, tensile strength and Young’s modulus, Density and Young’s modulus.

Table 6:Correlations

		UCS (MPa)	Tensile (MPa)	Young's modulus (GPa)	Density (kg/m3)	Poisson's ratio	Grain size (mm)
UCS (MPa)	Pearson Correlation	1,00	**0,585** **	**0,594** **	0,304**	0,485**	-0,274**
	Sig. (2-tailed)		0,000	0,000	0,000	0,000	0,009
	N	139	109	139	139	139	90
Tensile (MPa)	Pearson Correlation	**0,585** **	1,00	**0,624** **	**0,495** **	0,373**	-0,241*
	Sig. (2-tailed)	0,000		0,000	0,000	0,000	0,039
	N	109	109	109	109	109	74
Young's modulus (Gpa)	Pearson Correlation	**0,594** **	**0,624** **	1,00	**0,552** **	0,452**	-0,02
	Sig. (2-tailed)	0,000	0,000		0,000	0,000	0,871
	N	139	109	140	140	140	90
Density (kg/m3)	Pearson Correlation	0,304**	0,495**	**0,552** **	1,00	0,03	-0,09
	Sig. (2-tailed)	0,000	0,000	0,000		0,727	0,389
	N	139	109	140	140	140	90
Poisson's ratio	Pearson Correlation	0,485**	0,373**	0,452**	0,03	1,00	-0,12
	Sig. (2-tailed)	0,000	0,000	0,000	0,727		0,254
	N	139	109	140	140	140	90
Grain size (mm)	Pearson Correlation	-0,274**	-0,241*	-0,02	-0,09	-0,12	1,00
	Sig. (2-tailed)	0,009	0,039	0,871	0,389	0,254	
	N	90	74	90	90	90	90

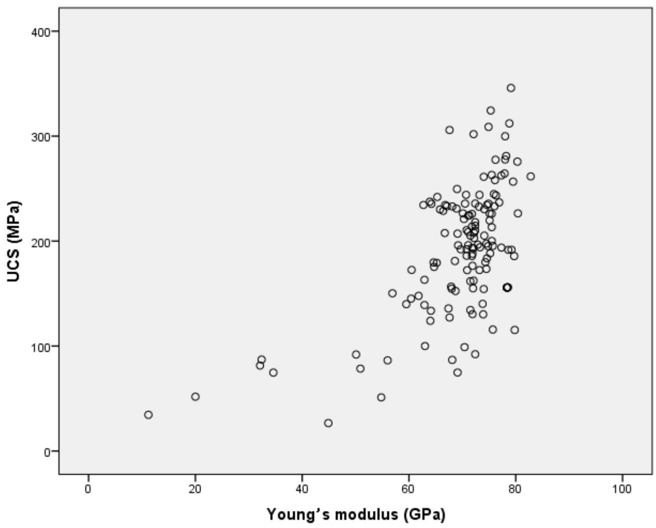
**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

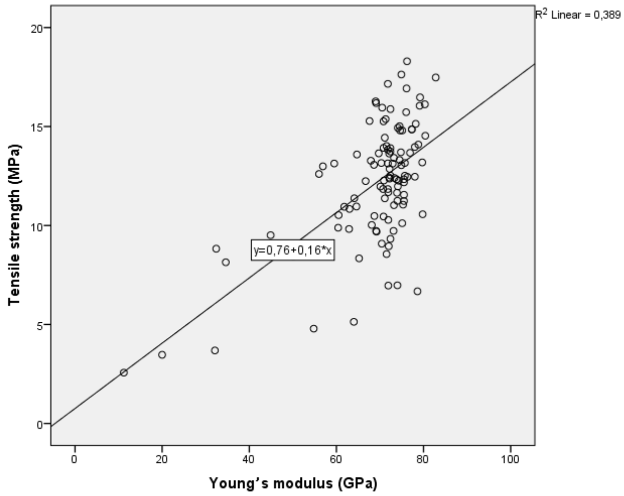
Such strong correlations between parameters may affect the multiple regression model. Building a model with the usage of independent parameters that are in a strong correlation with each other is doubtful. This phenomenon is called multicollinearity, and due to it this kind of analysis, it can describe specifically only the data that has been tested. With the independent parameters that strongly correlate between each other it will be reasonable to either exclude certain parameters from the multiple regression analysis model, or check the data using principal component analysis.

As can be seen from picture 13, a scatter plot of Young's modulus to UCS does not look linear, since there are two clearly drawn slopes: one from 0 to 60 GPa and the other from 60 GPa to 80 GPa. Thus, the use of pure Young's modulus data in linear multiple regression model does not look reasonably. However, it may be possible to analyze these two slopes separately, to test how well Young's modulus predicts UCS on low and on high values. Another way is to try to use Young's modulus with modification.

As can be seen from Picture 13, the main part of the values of the Young's modulus are distributed between 60 and 80 GPa. Picture 13 also shows that Young's modulus UCS values vary significantly with same values. Picture 14 shows scatterplot of Young's modulus to Tensile strength.

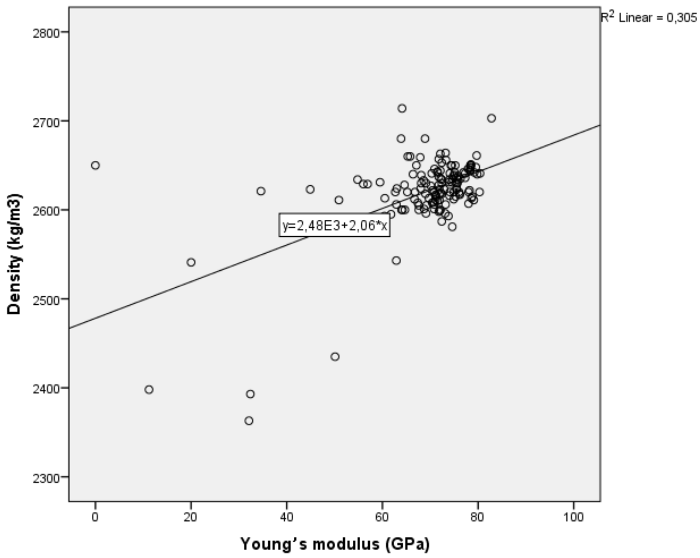


Picture 13. scatterplot of Young's modulus to UCS



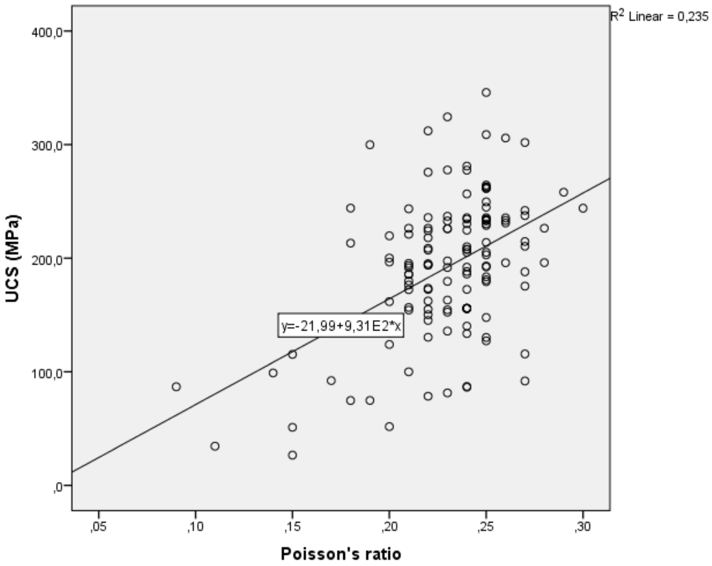
Picture 14. Scatterplot of Young's modulus to Tensile strength

As can be seen from picture 14, there are positive correlation between Young's modulus and tensile strength, in spite of the fact that Young's modulus values concentrate between 60 and 80 GPa. By concentration on the points, the scatterplot looks quite the same as Young's modulus to UCS presented in picture 13.



Picture 15. Scatterplot of Young's modulus to density of granite samples.

The scatter plot of Young's modulus to density presented in picture 15 shows a fairly compact cloud of points on high values of Young's modulus.



Picture 16. Scatterplot of Poisson's ratio to Density of granite samples.

However, the scatterplot of Poisson's ratio to UCS shown in picture 16 does not look convincing, even though there are some association. Most of the values of the Poisson's ratio spreads between 0.2–0.3 and values of UCS distributed quite widely.

Based on the table of correlations predicted equation of regression model:

$$UCS = \beta_0 + \beta_1 Tensile + \beta_2 Density + \beta_3 Poisson's + \varepsilon \tag{24}$$

UCS was defined as dependent variable and tensile strength, while density and Poisson's ratio as independent. Table 7 shows model summary.

Table 7: Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0,657[a]	**0,432**	0,416	49,4095

a. Predictors: (Constant),Poisson's ratio, Density, Tensile strength

As can be seen from Table 7, R-squared value is equal to 0.432, which means that the estimated model explained 43.2 % of the variation of dependent variable.

Table 8 shows that F-value of coefficient of determination is equal to 20.648 and is significant to 5% level.

Table 8:ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	195165,257	3	65055,086	**26,648**	**0,000[b]**
	Residual	256335,891	105	2441,294		
	Total	451501,148	108			

a. Dependent Variable: UCS

b. Predictors: (Constant), Poisson's ratio, Density, Tensile strength

Table 9: Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-408,444	297,420		-1,373	**0,173**
	Tensile strength	8,727	1,993	0,411	4,378	0,000
	Density	0,134	,115	0,102	1,167	**0,246**
	Poisson's ratio	628,320	154,275	0,332	4,073	0,000

a. Dependent Variable: UCS

As can be seen from Table 9, the intercept coefficient and the coefficient of density are not significant to 5 % level. It will be reasonable to try to exclude density out of model, and then check the model again.

The new equation of predicted model without density, can be modified as

$$UCS = \beta_0 + \beta_1 Tensile + \beta_2 Poisson's + \varepsilon \qquad (25)$$

Table 10: Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	**0,652[a]**	**0,425**	0,414	49,4939

a. Predictors: (Constant),Poisson's ratio, Tensile strength

As can be seen from table 10, value of R-square did not change noticeably in comparison to the previous model, and it is equal to 0.425, which means that the model explains 42.5 % of the variation of dependent variable.

Table 11:ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	191838,611	2	95919,305	**39,156**	**0,000[b]**
	Residual	259662,537	106	2449,647		
	Total	451501,148	108			

a. Dependent Variable: UCS

b. Predictors: (Constant), Poisson's ratio, Tensile

Table 11 shows that F-value of the coefficient of determination is equal to 39.156 and is significant to 5% level.

Table 12: Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	**-63,359**	32,732		-1,936	**0,056**
	Tensile strength	**9,972**	1,687	0,469	5,912	0,000
	Poisson's ratio	**586,135**	150,239	0,310	3,901	0,000

a. Dependent Variable: UCS

As can be seen from table 12, p-value of the intercept is not significant to 5 % level, but it is pretty close $p = 0.056$. The coefficients are presented below:

Intercept $\beta_0 = -63{,}359$

Coefficient of tensile strength $\beta_1 = 9{,}972$

Coefficient of Poisson's ratio $\beta_2 = 586{,}135$

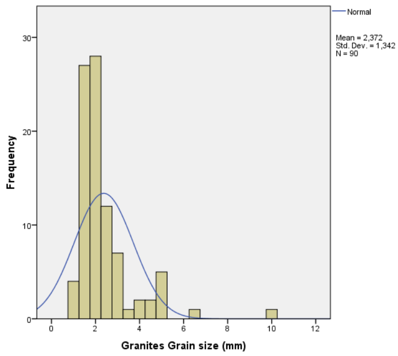
Than predicted equation of multiple regression model can be defined as

$$UCS = -63{,}359 + (9{,}972 \times Tensile) + (586{,}135 \times Poisson's\ ratio) \tag{26}$$

8.1.4 Analysis of the strength properties of the granite rock samples by different grain size

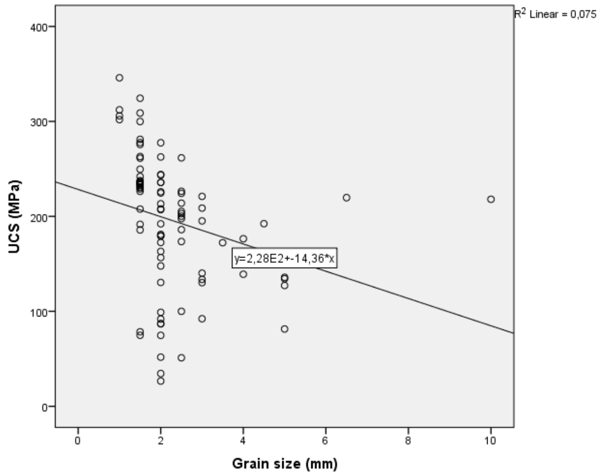
Next step is to analyze strength the properties of granite rock samples by their grain size. From the whole data on the grain size value or value intervals was reported only on a certain part of rock samples. Evaluation of the grain size of samples typically happens without any special equipment, just by eye. As a result, grain size of one particular sample can vary considerably, occasionally it is also not uniform and this explains the existence of intervals on the grain size data.

In this thesis from reported in laboratory grain size interval, for analysis, average value between two numbers was taken. Picture 17 shows the histogram of the available granite samples by grain size. Grain size values were recorded only for 90 of tested samples. As can be seen from Picture 17, the average grain size value shows two numbers and was equal to 2.37 mm.

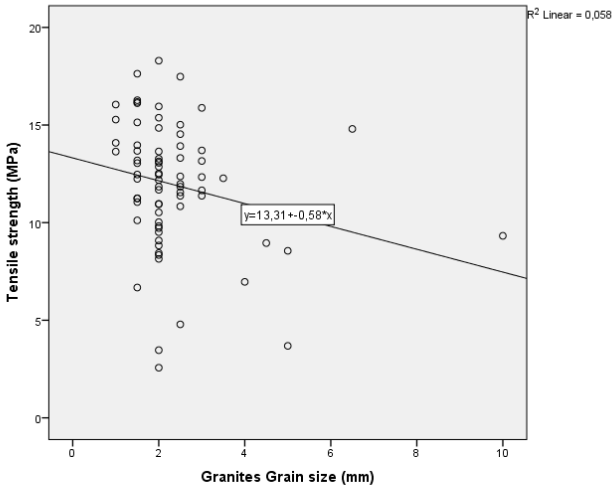


Picture 17. Histogram of grain size of granites

In picture 18, the scatter plot of grain size to UCS of granites is presented. As can be seen from Picture 18, most of the grain sizes of granites varies from 0.5–5 millimeters. It is also can be seen that uniaxial compressive strength varies significantly with relation to the obtained grain size; for example, the values of UCS vary from about 25 MPa to 275 MPa for 2 mm grain size rocks.



Picture 18. Scatter plot of average of grain sizes to UCS



Picture 19. Scatter plot of average values of grain sizes to UCS

As can be seen from pictures 18 and 19, the strength properties decrease with the increase of grain size. Moreover, the association on both pictures does not look quite well, and it may be possible that the inaccurate definition of grain size affects the results and shows in calculating the average for intervals. The poor quality of pictures is also possible due to a small number of tested coarse grain samples.

8.1.5 Analysis based on test observations

While testing the properties of geological structure, all unusual observations and uncommon failures must be unified as detected defects and recorded into comments. This practice allows to analyze them in more detail later on. Based on such comments in the the leftmost column done on the Laboratory data, some interesting facts were dicsovered for the analysis of mechanical properties from the group of samples with hair cracks and cavities.

Table 13 separates and shows the basic descriptive statistics of only those samples of granites where the hair cracks were marked. There were 10 samples with marked hair cracks identified. As have been noticed during the measurement, only 4 of 10 specimens broke along the hair crack. Uniaxial compressive strength values of 7 samples with hair cracks were less than 100 MPa.

Table 13: Descriptive statistics of tested granite samples with hair cracks

	Density (kg/m3)	**UCS (MPa)**	**Young's modulus (GPa)**	**Poisson's ratio**	**Tensile str (MPa)**	**Average Grain Size (mm)**
Average	2614,3	**100,2**	57,0	0,18	9,0	1,95
Min	2540,6	26,6	20,0	0,09	3,5	1,50
Max	2639,1	226,3	78,6	0,24	16,2	3,0
Standard deviation	28,0	61,6	18,5	0,04	3,65	0,47

From the group, there were 3 samples marked as having cavities and 1 with small cavities. The measured uniaxial compressive strength of the sample with small cavities was equal to 163,1 MPa, and the average value of UCS of other two samples marked as having cavities was equal to 84 MPa.

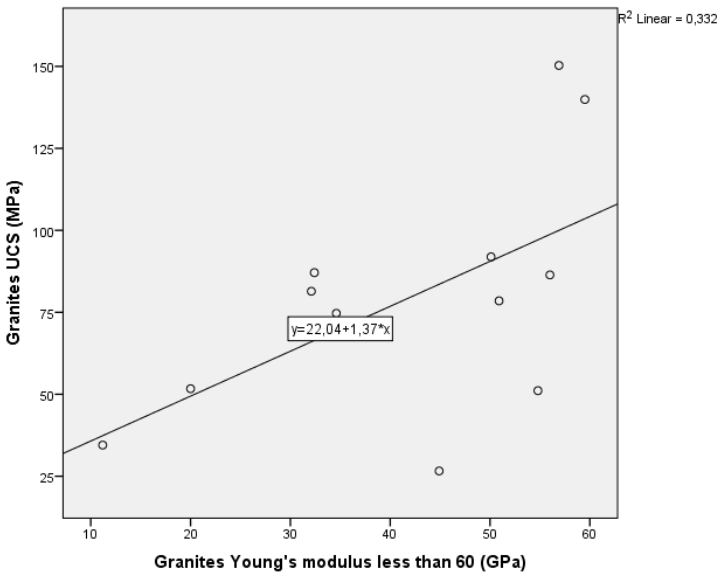
8.1.6 Slopes of Young's modulus

Referring to the scatter diagram of Young's modulus values to UCS of tested granites presented in Picture 13, obtained data were divided into two parts: demonstrating low and high values of Young's modulus. For the analysis of dependence between Young's modulus values and uniaxial compressive strength of tested granites, those samples with the values of Young's modulus lower than 60 GPa were separated into one group. The group with Young's modulus values greater than 60 GPa were assembled into another group. Basic descriptive statistics of the first group of the samples is presented in Table 14. From all these samples shown in Table 14, UCS test was done for 12 specimens and Brazil test for 11.

Table 14: Descriptive Statistics of granites with Young's modulus less than 60 GPa

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	12	26,6	150,3	**79,5**	10,8	37,4
Young's modulus (Gpa)	12	11,2	59,5	**41,9**	4,5	15,7
Tensile strength (MPa)	11	2,6	13,1	**8,0**	1,2	3,9

As can be seen from Table 14, average values of UCS and tensile strength are also quite small. Picture 20 shows scatter plot of Young's modulus to UCS.



Picture 20: Scatter plot of Young's modulus to UCS

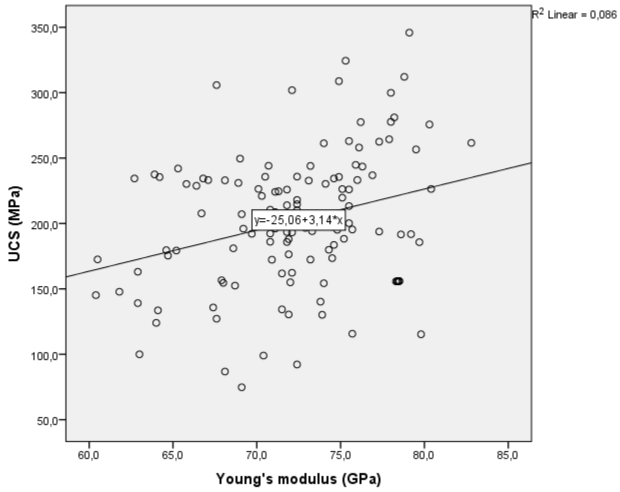
As can be seen from picture 20, the scatter plot shows a linear association between Young's modulus with the values less than 60 GPa to UCS of the granites of 12 tested granite samples.

From this observed group of 12 samples, the values of UCS were lower than 100 MPa for 10 specimens. From this 10 specimens, the rock samples on 8 were also marked with comments about their structural defects, cracks, cavities and rock weathering.

Therefore, dependence between UCS and the values of Young's modulus greater than 60 GPa was checked further, descriptive statistics of this second group is shown in Table 15.

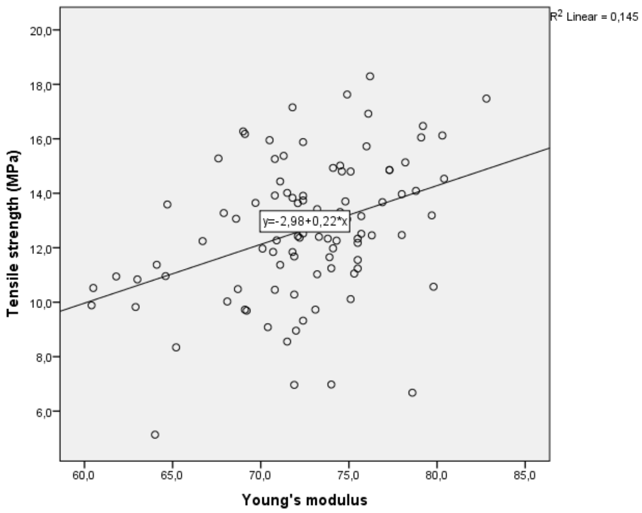
Table 15: Descriptive Statistics of granites with Young's modulus more than 60 GPa

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	127	74,8	345,9	**201,9**	4,6	51,8
Young's modulus GPa	127	60,4	82,8	**72,2**	0,43	4,8
Tensile stremgth (MPa)	98	5,1	18,3	**12,7**	0,26	2,6



Picture 21. Scatterplot of Young's modulus (60- Gpa) to UCS

As seen from Table 15 and picture 21, the association between the high values of Young's modulus and the values of uniaxial compressive strength is weak (picture 21), R-squared value is equal only to 0.086, which can be seen in the right upper corner of Picture 21. Picture 22 shows scatterplot of hight values of Young's modulus to Tensile strength.



Picture 22. Scatterplot of Young's modulus (60- GPa) to Tensile strength

As seen from picture 22, the association between the values of the Young's modulus greater than 60 GPa and tensile strength is better than on the previous picture, but still not quite strong (pictures 21 and 22).

Based on the results shown in pictures 20 and 21, it can be assumed that the low Young's modulus values may predict the uniaxial compression strength, but the qualitative difference between the number of samples does not allow for to make a definite conclusions.

8.2 Gneiss

Analysis proceeds with examination of the gneiss rocks. There were tested more than 10 different gneiss rocks were tested which were collected from 19 different locations in Finland and one with 8 samples from Norway.

As can be seen from Table 16, in total there were 146 samples tested for UCS and only 89 were also tested for tensile strength. The basic descriptive statistics of all gneiss samples are shown in Table 16.

Table 16: Descriptive statistics all gneisses

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	146	50,7	341,3	**170,6**	5,47	**66,1**
Tensile Str (MPa)	**89**	3,3	29,7	**15,95**	0,55	**5,2**
Young's modulus (GPa)	146	33,2	114,2	71,0	1,33	16,1
Poisson's ratio	146	0,14	0,45	0,23	0,0033	0,04
Density (kg/m3)	146	2605	3277	2748	9,25	112

The largest group of the gneiss rocks that have been tested contained 63 samples, and it was mica gneiss rocks. Descriptive statistics of tested mica gneiss rocks are presented in Table 17. As can be seen from table 17, the average value of UCS is lower than on the average of all tested gneiss rocks, otherwise the average tensile strength is slightly higher (table 17).

The second largest group with 18 tested samples was just marked as gneiss rocks. Descriptive statistics of this group is presented below in Table 18. As can be seen from table 18, the values in this group slightly differ from the whole data that was presented in table 15. In this group, Young's modulus and density are slightly lower.

Table 17:Descriptive Statistics Mica Gneisses

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	**63**	53,2	332,5	**159,8**	8,4	67,0
Tensile Str (MPa)	**37**	7,4	29,7	**17,6**	0,87	5,3
Young's modulus (GPa)	63	36,6	114,2	69,6	2,2	17,6
Poisson's ratio	63	0,14	0,39	0,24	0,005	0,04
Density (kg/m3)	63	2628	3277	2777	13,3	106

Table 18: Descriptive Statistics of rocks marked Gneiss

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	18	51,2	279,5	**161,6**	14,6	61,8
Tensile Str (MPa)	8	7,9	11,4	**9,6**	0,40	1,1
Young's modulus (GPa)	18	33,2	64,7	56,5	2,1	8,8
Poisson's ratio	18	0,15	0,45	0,24	0,014	0,06
Density (kg/m3)	18	2617	2752	2680	10,5	44,4

The third largest group of tested gneiss rocks is granitic gneiss rocks with 15 samples. Descriptive statistics for this group is presented below in Table 19. These granitic gneiss rocks were collected from three different locations, as can be seen from Table 19. They demonstrate that their average value of UCS differs significantly from the whole data statistics, with the difference for UCS reaching about 32%.

Table 19: Descriptive Statistics Granitic Gneisses

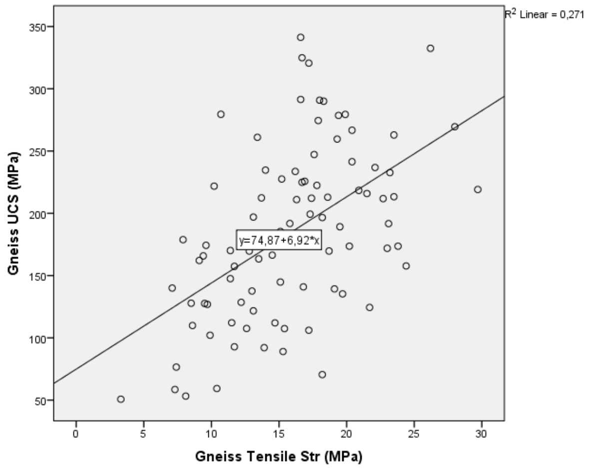
	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	**15**	138,4	341,3	**225,1**	15,9	61,7
Tensile Str (MPa)	6	13	17	**15,7**	0,65	1,6
Young's modulus (GPa)	15	72,3	83,5	77,5	0,8	3
Poisson's ratio	15	0,17	,28	0,24	0,007	0,03
Density (kg/m3)	15	2608	2726	2648,6	8,9	34,5

The spread of uniaxial compressive strength results and tensile strength results are presented in pictures 23 and 24 (in Appendix 1). As can be seen from these pictures, the spread is quite near normal. Finally, the linear correlation results between the obtained data of all parameters of the tested gneiss rocks presented in table 20 (in Appendix 1).

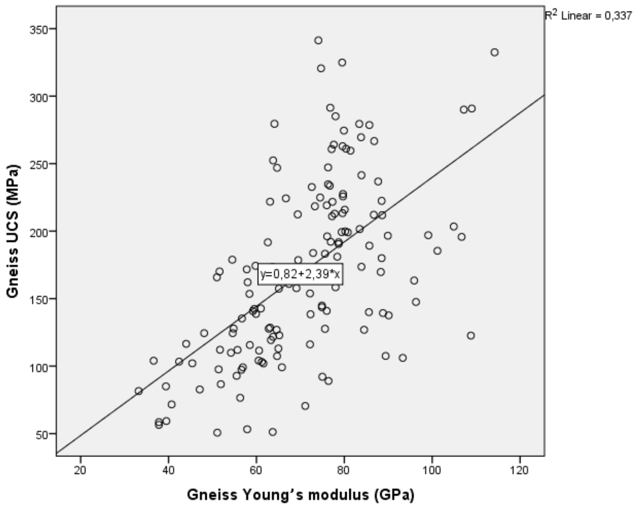
As can be seen from table 20, significant positive correlation is measured between UCS and tensile strength and UCS and Young's modulus, with tensile strength and Young's modulus *r=0.429* and between Young's modulus and density *r=0.473*.

Summing up, the analysis of correlations for individual groups for mica gneisses shows positive significant correlations between UCS and tensile strength *r=0.678*, UCS and Young's modulus *r=0.798*, Young's modulus and density *r=0.544*. Thus, for the tested rock samples marked as Gneiss a positive significant correlation has been identified between UCS and Young's modulus, tensile strength and Poisson's ratio.

On the contrary, for granitic gneiss group, a significant negative correlation has been measured between tensile strength and density r is equal to –0.890 for 6 samples; while the correlation coefficient between Young's modulus and density was equal to 0.762 for 15 tested samples. Thus, the obtained correlation coefficient between tensile strength and UCS of tested granitic gneiss rock was strong but not significant. Picture 25 shows scatter plot of Tensile strength to UCS of all tested gneiss rocks. Picture 26 shows scatter plot of Young's modulus to UCs of all tested gneiss rocks.



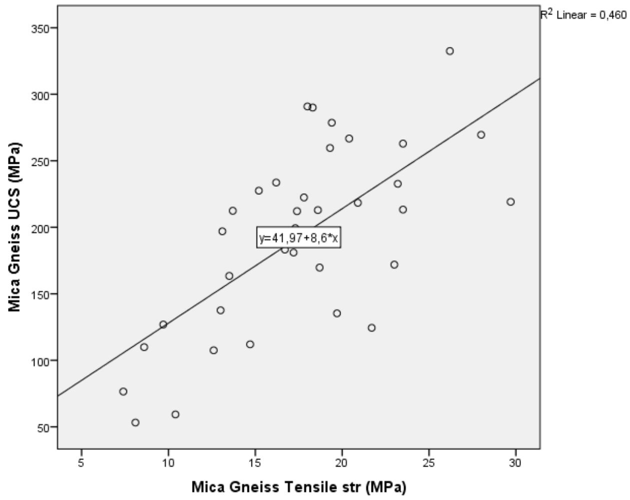
Picture 25. Scatterplot of Tensile strength to UCS of all tested gneiss rocks



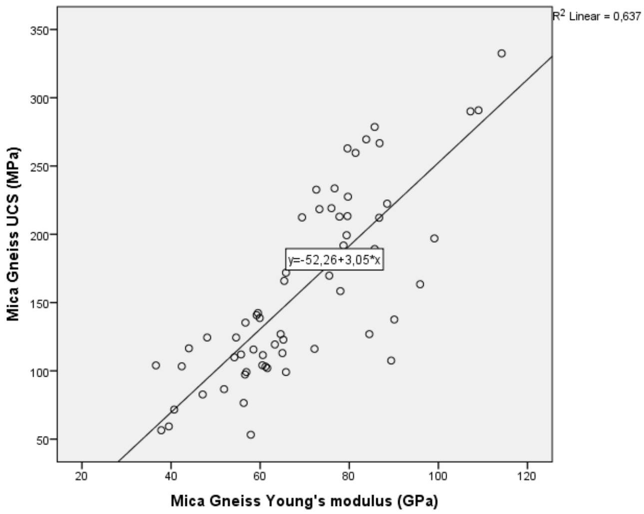
Picture 26. Scatter plot of Young's modulus to UCS of all tested gneiss rocks

As seen from pictures 25 and 26, there is a linear positive association between tensile strength and Young's modulus to UCS of all tested gneiss rocks. However, as can be seen from Picture 27 (given in Appendix 1), the scatter diagram of Poisson's ratio to UCS of all tested Gneiss rocks shows no linearity.

The scatter diagrams of parameters of tested mica gneiss rocks are presented in Pictures 28 and 29. As can be seen from these pictures, the association is positive for both diagrams.



Picture 28. Scatterplot of Tensile strength to UCS of tested mica gneiss rocks



Picture 29. Scatter plot of Young's modulus to UCS of tested mica gneiss samples

Finally, picture 30 (presented in Appendix 1) shows the scatter diagram for the density to UCS of tested mica gneiss rocks. This scatter diagram shows no linearity. On the contrary, the scatter diagram for density and Young's modulus of tested granitic gneiss rocks (presented in picture 31 of Appendix 1), shows a quite strong positive association.

8.2.1 Multiple linear regression for all tested gneiss rocks

The predicted equation for multiple regression for gneiss rocks can be defined as:

$$UCS = \beta_0 + \beta_1 Tensile + \beta_2 Young's + \beta_3 Density + \varepsilon \qquad (27)$$

In this equation , UCS was defined as dependent variable and Tensile strength, Young's modulus and density as independent. Table 21 shows model summary.

Table 21: Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0,689[a]	**0,475**	0,457	50,6

a. Predictors: (Constant), Density, Tensile strength, Young's modulus

As can be seen from table 21, the model summary R-square value is equal to 0.475 which means that the estimated model explained 47.5 % of the variation for dependent variable.

Further on, table 22 (given in Appendix 1) shows that F-value of the coefficient of determination is equal to 25.667 and is significant to 5% level. Finally, as can be seen from table 23 (presented in Appendix 1), all coefficients are significant to 5% level. It may be assumed that these strong results might have been affected by a particularly strong correlation between tensile strength and Young's modulus parameters presented in table 20 (given in Appendix 1).

8.2.2 Multiple linear regression for tested mica gneiss rocks

This chapter expore multiple linear regression between obtained parameters of only mica gneiss rocks. Construction of the multiple regression model only for the mica gneiss samples shows much better results. Due to multicollinearity, model is constructed without density. Simple correlation results of tested mica gneiss rocks samples are presented in Table 24 in appendix 1. Equation of regression model can be defined as:

$$UCS = \beta_0 + \beta_1 Tensile + \beta_2 Young's + \varepsilon \qquad (28)$$

Table 25 shows model summary, as can be seen R-squared value is equal to 0.760. From Tables 26 and 27 presented in appendix 1, can be seen that F-value is bigger than zero and all coefficients were also significant for 5% level.

Table 25:Model Summary

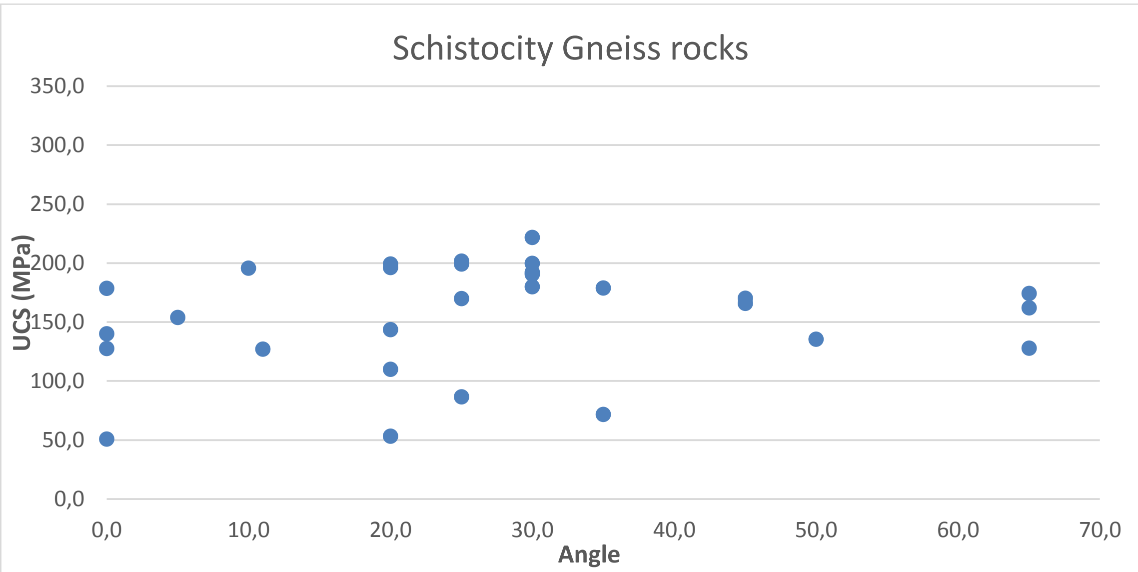
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0,872[a]	**0,760**	0,746	34,0144

a. Predictors: (Constant), Young's modulus, Tensile strength

Construction of similar regression models for the Granitic gneisses and Gneisses groups does not reveal significant results.

8.2.3 Dependence of strength to the angle of Schistosity of Gneiss rocks

This chapter expore the dependence of strength to the angle of schistosity (angle between schistosity plane and loading direction) of tested Gneiss rocks. Variation of gneiss rocks strength to angle of schistosity is presented in Picture 32. As can be seen from Picuture 32, the results were not informative in relation to the theory briefly discussed in chapter *Anisotropy and inhomogeneity*. The reason for this result may be due to material differences between gneiss rocks and a quite small group of observed samples.



Picture 32. UCS of tested gneiss rocks with respect to schistosity angle

8.3 Gabbro

This chapter explore data of tested Gabbro rocks. The results for the uniaxial compressive strength test for gabbro rocks were obtained from only 21 samples and only 17 from it were also tested for tensile strength. Of the whole group only 9 samples were identified as gabbro, besides were also tested 7 samples of marginal gabbro (upper, lower and central) and one sample that were named as Hybrid gabbro. Descriptive statistics of all 21 samples are presented in Table 28.

Table 28: Descriptive Statistics Gabbro rocks

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	21	73,2	442,4	**190,5**	25,0	**114,8**
Tensile Strenght (MPa)	17	10,3	23,9	**15,5**	0,94	3,9
Young’s modulus (GPa)	21	56,6	107,1	83,9	3,3	15,2
Poisson’s ratio	21	0,21	0,35	0,27	0,008	0,04
Density (kg/m3)	21	2823	3143	**2962**	17,9	82,2

Spreads of uniaxial compressive strength and tensile strength results presented in histogram Pictures 33 and 34 are given in appendix 2. As can be seen from Picture 33 spread of values of UCS is quite high, this explains the extremely high value of standard deviation presented in Table 27.

Linear correlations of the parameters presented in Table 29 in appendix 2, as can be seen there are positive strong significant correlation between UCS and tensile strength, UCS and Young’s modulus and UCS and density. Besides tensile strength correlates with Young’s modulus and Young’s modulus with density. Problem of multicollinearity is up again due to such strong correlation between parameters. For the construction of multiple regression model, exclusion of some parameters is required. Scatter plots of the relationships between parameters are presented in appendix 2 in Pictures 35 to 38.

8.3.1 Multiple linear regression for tested gabbro rocks

Based on Table of correlations predicted equation of regression model defined as:

$$UCS = \beta_0 + \beta_1 Tensile + \beta_3 Density + \varepsilon \quad (29)$$

UCS was defined as dependent variable and tensile strength and density as independent.

Table 30:Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0,826[a]	**0,682**	0,636	72,8

a. Predictors: (Constant), Gabbro Density, Gabbro Tensile strength

Table 30 shows model summary, R-squared value is equal to 0.682 and this means that estimated model explained 68.2 % of the variation of dependent variable.

Table 31 given in appendix 2, shows that F-value is equal to 14.99 and is significant to 5% level.

Table 32 presented in appendix 2, shows that intercept coefficient and coefficient of density are not significant to 5 % level, but are pretty close.

Accordingly, from Table 32 estimated model of multiple regression for gabbro rocks can be derived by the equation:

$$UCS = -1381 + (21.5 \times Tensile) + (0{,}422 \times Density) \quad (30)$$

8.4 Diorite

This chapter explore data of tested diorite rock samples. In total, 39 samples diorite rocks were tested for uniaxial compression. Out of these 39, only 24 samples were also tested for tension strength by Brazil test. Rock samples were collected from 9 different regions of Finland. From the whole group of tested diorite samples, 9 samples were named quartz diorite and 6 others ore zone diorites. Descriptive statistics of all data separated by names is presented in Tables 33–37. From the group of 24 tested samples of “pure” diorite, according to the testing notes, a group of 12 specimens were fully saturated. Descriptive statistics of the test results for this group are presented in tables 36 and 37. The saturated samples, however, were not tested for tensile strength.

Table 33: Descriptive statistics of whole tested Diorite rocks data (Diorite, quartz diorite, ore zone diorite)

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	39	84,8	284,7	**161,8**	8,0	**50,2**
Tensile Strength (MPa)	24	11,3	17,7	**15,1**	0,38	1,89
Young's modulus (GPa)	39	50,8	97,9	**71,6**	1,8	11,2
Poisson's ratio	39	0,21	0,35	0,27	0,005	0,033
Density (kg/m3)	39	2714	2979	2803	10,2	63,9

Table 34: Descriptive Statistics of quartz diorite

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	9	135,1	264,8	**203,8**	13,3	**39,9**
Tensile Str (MPa)	9	11,5	16,9	**15,16**	0,6	1,9
Young's modulus (GPa)	9	57,9	85,8	77,3	3,3	9,8
Poisson's ratio	9	,23	,29	0,26	0,006	0,02
Density (kg/m3)	9	2715	2846	2765	16,7	50,2

Table 35:Descriptive Statistics ore zone diorite

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	6	136,5	161,7	**152,9**	5,2	**12,7**
Tensile Str (MPa)	6	15,5	17,2	**16,1**	0,35	0,87
Young's modulus (GPa)	6	67,5	78,8	74,3	2,2	5,4
Poisson's ratio	6	0,24	0,27	0,25	0,006	0,013
Density (kg/m3)	6	2820	2840	2831	3,7	9,2

As can be seen from tables 34 and 35, the differences of average values of UCS were quite significant between the quartz diorite and ore zone diorite samples. Differences in strength of tested diorites are shown in table 36. Differences in strength for the fully saturated diorites are shown in table 37, and in this case, they are quite noticeable.

Table 36:Descriptive Statistics of Diorite rocks

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	12	84,8	284,7	**169,1**	18,3	**63,3**
Tensile Strength (MPa)	9	11,3	17,7	**14,5**	0,75	2,2
Young's modulus (GPa)	12	63,0	97,9	**77,2**	3,2	11,0
Poisson's ratio	12	0,21	0,29	0,26	0,0058	0,02
Density (kg/m3)	12	2724	2979	2824	23,9	82,8

Table 37: Descriptive statistics of fully saturated diorite rocks

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	12	88,3	170,1	**127,3**	7,2	25,0
Young's modulus (GPa)	12	50,8	66,3	**60,3**	1,43	5,0
Poisson's ratio	12	0,27	0,35	0,31	0,008	0,027
Density (kg/m3)	12	2714	2866	2796	16,3	56,6

Results of linear correlation are presented in table 38 (in Appendix 3). It can be seen from table 38 that the correlations between diorite sample parameters are quite weak. A strong positive significant correlation was measured only between UCS and Young's modulus, as shown in picture 40 (in Appendix 3). Between Poisson's ratio and Young's modulus, there was, however, a negative value of correlation coefficient measured.

Finally, the scatter plot diagrams of the test results of diorite rock samples are presented in pictures 39–42 (in Appendix 3). As seen from picture 39, the linear association between tensile strength and UCS is weak (picture 39). The associations between Poisson's ratio to UCS and density to UCS are also not linear and using them in a linear regression model will not be correct (pictures 41 and 42).

8.4.1 Multiple linear regression for tested diorite rocks

In this chapter multiple linear regression was applied to predict uniaxal compressive strength of obtained parameters of diorite rocks. To conduct this analysis, UCS was defined as a dependent variable and Tensile strength and Young's modulus as independent. As a result, the equation of regression line can be defined as:

$$UCS = \beta_0 + \beta_1 Tensile + \beta_3 Young's\ modulus + \varepsilon \tag{31}$$

Table 39 presents the summary of multiple regression model for diorite rocks.

Table 39:Model Summary Diorite

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0,710[a]	**0,504**	0,457	37,2332

a. Predictors: (Constant), Young's modulus, Tensile strength

As can be seen from table 39, R-squared value is equal to 0.504 which means that the estimated model explained 50.4 % of the variation of dependent variable.

As can be seen from the ANOVA table 40 (given in Appendix 3), F-value is equal to 10.7 and is significant to 5% level. Table 39 also shows that R-squared value looks convincing, but based on the results from table 41 (in Appendix 3), the coefficients of tensile strength and intercept are no significant. It especially concerns the coefficient of tensile strength with p-value equals to 0.435.

Multiple linear regression analysis of only the diorites data, (quartz diorite and ore zone diorite were excluded), shows almost the same result as for the whole data. The obtained R-squared value were strong and equal to 0.795 but tensile strength coefficient was not significant, the obtained p-value was equal to 0.516.

8.5 Granodiorite

This chapter explore the data of tested granodiorite rocks. In total, 15 samples of granodiorite rocks were tested for uniaxial compression. Out of these 15, only 3 samples were also tested for tension strength by Brazil test. Table 42 shows the average UCS value of granodiorite rocks. As can be seen from table 42, the average UCS value of granodiorite rocks are quite small. It can probably be explained as the result of insufficient number of performed tests. Rock samples were collected from 4 different regions of Finland.

Table 42: Descriptive Statistics Granodiorite

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	15	87	190,7	**132,0**	7,4	**28,5**
Tensile Strength (MPa)	**3**	12,4	14,2	**13,2**	0,5	0,92
Young's modulus (GPa)	15	41,1	80,1	**61**	2,7	10,4
Poisson ratio	15	0,17	0,27	0,22	0,008	0,03
Density (kg/m3)	15	2693	2761	2713	4,4	17,2

In addition, Table 43 (in Appendix 4) shows the correlations between the obtained tests parameters. As can be seen from Table 43, the results of a simple linear correlation for granodiorite parameters are quite weak. Most likely, only three obtained tests for tension strength make relationship between tensile strength and UCS of tested granodiorites negative. Table 43 shows a strong positive correlation only between the test results of UCS and Young's modulus.

Scatter diagram of Young's modulus to UCS and scatter diagram of density to UCS are presented in Pictures 43 and 44 in appendix 4.

Constructed multiple regression analysis model showed no significant results for granodiorite rocks data.

8.6 Amphibolite

This chapter explore the data of tested amphibolite rocks. In total, 36 samples of amphibolite rocks were tested for uniaxial compression, of which only the results for 35 were eventually available. Out of these 35, only 29 specimens were also tested for tension strength by Brazil test. Amphibolite rock samples were collected from 15 different locations in Finland. Descriptive statistics of tested amphibolite rocks are presented in table 44.

Table 44: Descriptive Statistics of amphibolite rocks

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	**35**	95,3	395,6	**201,1**	**10,9**	64,6
Tensile Strength (MPa)	**29**	8,5	22,5	**16,9**	0,6	3,29
Young's modulus (GPa)	36	56,8	119,3	**91**	2,55	15,32
Poisson ratio	36	0,16	0,34	0,26	0,00571	0,034
Density (kg/m3)	36	2715	3212	**2968**	19,8	118,8

Additionally, the spread of result of uniaxial compression strength and tensile strength in pictures 45 and 46 (in Appendix 5). This spread is quite near normal for so small a number of tested specimens.

Finally, the results of a simple linear correlation between the obtained test parameters of amphibolite rocks are presented in table 45 (Appendix 5). It shows that the linear correlation results for the tested parameters of amphibolite rocks look rather weak, so that the correlation coefficient between UCS and tensile strength equals to 0.439 and is significant to 5% level. However, a positive strong significant correlation was obtained between Density and Young's modulus. The scatter diagram for the tensile strength and UCS is presented in picture 47 (in Appendix 5). Picture 48 (given in Appendix 5) also shows a weak association between Young's modulus and UCS of tested amphibolite rocks.

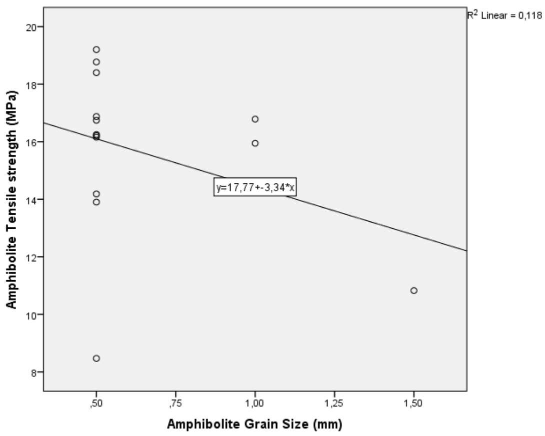
8.6.1 Multiple linear regression for tested amphibolite rocks

In this chapter multiple linear regression was applied to predict uniaxal compressive strength of obtained parameters of amphibolite rocks. As the results show, the constructed multiple regression model demonstrates no significant results. The association between Poisson's ratio – UCS and Density – UCS were not linear; and the model construction as dependent UCS and independent Tensile strength and

Young’s modulus showed no significant result. The obtained R-square value for the model was equal only to 0.194.

8.6.2 Dependence of strength properties to the grain size of the tested amphibolite rocks

This chapter explore dependence of strength to the grain size of tested samples of amphibolite rocks. From all 36 tested amphibolite samples, the grain sizes of only 14 were recorded. The grain size of 9 samples was noted as less than 1 mm; for two other samples the grain size value were defined as equal to 2 mm, and for one sample between 1–2 mm. The average UCS of samples with the grain size of less than 1 mm was measured equal to about 200 MPa, and the average tensile strength to 15.9 MPa. Thus, the variance between the grain size and UCS of tested amphibolite rock samples shows an extremely week negative relationship.



Picture 49. Scatter plot of grain size to tensile strength.

Approximately same results were obtained between the values of grain size and the tensile strength results (picture 49), but it was noticed that tensile strength decreases with with the increase in grain size. However, the number of the recorded grain size parameters of tested samples is not sufficient for any reliable conclusions.

8.7 Pyroxenite

This chapter explore the data of tested pyroxenite rocks. Pyroxenite rocks were tested for uniaxial compression in total of 11 samples. Out of these 11, only 5 samples were also tested for tension strength by Brazil test. These rock samples were collected from 3 different regions of Finland: 4 samples from Site 1, 3 samples from Site 2 and 4 samples from Site 3. The obtained average value of UCS from Site 1 for the pyroxenite rock samples was equal to 97 MPa; the average UCS value of olivine pyroxenite from Site 3 was equal to 251 MPa; and the average UCS value of pyroxene from Site 3 was 127,4 MPa. Tensile strength were measured for 3 olivine pyroxenite samples from Site 2 and the average value was equal to 17.4 MPa. Descriptive statistics of tested pyroxenite rocks are presented in table 46.

Table 46: Descriptive Statistics of tested pyroxenite rocks

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	11	50,5	263	**150**	22,2	**73,6**
Tensile Strenght (MPa)	**5**	12,6	19,7	**15,6**	1,25	2,8
Young’s modulus (GPa)	11	45,8	122,2	**78,6**	9,3	30,8
Poisson ratio	11	0,19	0,32	0,25	0,012	0,04
Density (kg/m3)	11	2749	3212	**3010,4**	40,8	135,2

Results of simple linear correlations between measured parameters of tested pyroxenite rocks are presented in Table 47 of appendix 6. There is a strong positive linear significant correlation between UCS and Young’s modulus, UCS and density and between density and Young’s modulus. Scatter plots between different parameters of pyroxenite rocks are presented in Pictures 50–52 of appendix 6.

As can be seen in Pictures 50–52, though linear relationship is strong, insignificant number of performed tensile stress test raise the doubts. Dependence between Young’s modulus and UCS looks linear, and as shown in Picture 51, a big group of the points situated between 40–60 GPa, and second cluster can be seen on high 120 GPa rates. Similar trend can also be seen in Picture 52 variance of density to UCS, smaller values of density represent lower values of UCS and higher density also higher numbers of UCS. These three samples which can be seen in Pictures 51 and 52 with significantly high values are results of tested olivine pyroxene samples.

8.8 Schist

This chapter explore the data of tested schist rocks. Descriptive statistics of all tested schist rocks are presented in Table 48. From the whole group of 18 samples tested for UCS and 17 samples tested for tensile strength, can be separate out a group of 7 tested mica schist samples and 4 samples of black schist (metamorphosed black shales). Descriptive statistics of tested mica schist samples and black schist samples are presented in Tables 49 and 50.

Table 48: Descriptive Statistics of all schist rocks

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	18	35,3	194,2	**112,8**	11,9	**50,5**
Tensile Strength (MPa)	17	4,6	20,4	**12,6**	1,28	5,3
Young’s modulus (GPa)	18	38,6	86,4	67,0	2,5	10,7
Poisson ratio	18	,00	,31	0,18	0,02	0,09
Density (kg/m3)	18	2702	2849	2769,3	10,3	43,5

As can be seen from Tables 48 and 49 difference between UCS of the whole group and mica schist rocks is quite noticeable. It is more evident between average values of tensile strength.

Table 49: Descriptive Statistics of tested mica schist rocks

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	7	66,7	158,8	**121,2**	14,8	**39,1**
Tensile Strength (MPa)	6	10,9	20,4	**16,8**	1,5	3,6
Young’s modulus (GPa)	7	54,9	78,6	71,5	3,0	8,1
Poisson ratio	7	0,15	0,31	0,23	0,018	0,05
Density (kg/m3)	7	2731	2819	2757	13,7	36,1

As can be seen from Table 50, average values of UCS of tested black schist rocks are much bigger than average UCS of whole group statistics, and also considerably different from the mica schist test results.

Table 50: Descriptive Statistics of tested black schist

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	4	118,3	194,2	**161,8**	19,1	38,3
Tensile Str (MPa)	4	10,8	19,7	**14,9**	1,8	3,7
Young's modulus (GPa)	4	61,6	69,9	66,6	1,9	3,9
Poisson ratio	4	0,20	0,28	0,24	0,02	0,03
Density (kg/m3)	4	2781	2849	2803	15,6	31,3

Results of the simple correlation between parameters of tested schist rocks are presented in Table 51 of appendix 7. There are significant positive linear correlation between UCS and Tensile strength, UCS and Young's modulus, UCS and Poisson's ratio, Tensile strength and Poisson's ratio (Table 51). Simple linear correlation only for mica schist showed no significant linear correlation results. Scatter diagrams are presented in Pictures 53–57 and given in appendix 7.

8.8.1 Multiple linear regression for tested schist rocks

Construction of the multiple regression model presented below, based on scatter plots 55, 56, 57 and Table of correlations Poisson's ratio and density were excluded from the model. Equation of predicted regression model can be defined as:

$$UCS = \beta_0 + \beta_1 Tensile + \beta_2 Young's + \varepsilon \quad (32)$$

UCS is defined as dependent variable and Tensile strength, Young's modulus as independent.

Table 52:Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0,749[a]	**0,561**	0,499	36,7

a. Predictors: (Constant), Young's modulus, Tensile strength

Model summary, R-squared value is equal to 0.561 and this means that estimated model explained 56.1 % of the variation of dependent variable (Table 52).

Table 53 given in appendix 6 shows that F-value is equal to 8.95 and is significant to 5% level.

Based on results of Table 54 given in appendix 6 predictive model of multiple regression for schist rocks can be defined as:

$$UCS = -85.3 + (4{,}84 \times Tensile) + (2{,}07 \times Young's) \qquad (33)$$

Coefficient of tensile strength and coefficient of Young's modulus are significant to 5% level, however coefficient of intercept (constant) are not statistically significant to 5% level, but not far away (Table 54).

8.9 Leptite

This chapter explore the data of tested leptite rocks. There were only 14 leptite rock samples tested for UCS and of these only 7 specimens were also tested for tensile strength. In total 8 samples had been obtained from Finland, one from Otaniemi and 7 specimens from site 4, another 8 samples had been collected from Sweden, site 5. As can be seen from Table 55 average UCS value is less than 100 MPa.

Uniaxial compressive strength of the samples collected from Otaniemi is equal to 195.4 MPa. The average of all samples collected from site 4 is equal to 104.7 MPa and average value of samples from site 5 is equal to 60.8 MPa.

Table 55: Descriptive Statistics of tested leptite rocks

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	14	25,1	195,40	**92,3**	12,8	**47,7**
Tensile Strength (MPa)	7	9,5	18,88	**13,9**	1,8	3,4
Young's modulus (GPa)	14	8,1	82,80	45,2	6,0	22,6
Poisson ratio	14	0,05	,29	0,18	0,017	0,07
Density (kg/m3)	14	2629	3097	2840,9	36,3	135,8

Table 56 given in appendix 8 presents simple correlations between parameters of tested leptite rocks. UCS is significant with all parameters, and as can be seen correlation coefficient between UCS and density is negative. Results presented in Table 55 allude to the problem of multicollinearity for multiple linear regression model. Correlations ratios between parameters are so extremely strong, that multiple regression model will most likely show fine results, but unfortunately conclusions concern only this group of tested leptite samples. Scatter plots of tested parameters are given on Pictures 58–62 in appendix 8.

8.10 Quartzite

This chapter explore the data of tested quartzite rocks. Uniaxial compression strength results for quartzite rocks were obtained from 15 tested specimens and from those only 4 samples were also tested for tension strength by Brazil test. Descriptive statistics of obtained test results is presented in Table 57.

Table 57: Descriptive Statistics Quartzite

	N	Minimum	Maximum	Average	Std. Error	Std. Deviation
UCS (MPa)	15	114,1	336,8	**190,6**	20,2	78,3
Tensile Strength (MPa)	**4**	12,2	16,3	**14,8**	0,94	1,87
Young's modulus (GPa)	15	40,3	93,8	71,8	4,24	16,4
Poisson ratio	15	0,07	0,53	0,21	0,04	0,14
Density (kg/m3)	15	2588	2793	2663	12,6	48,6

Table of simple linear correlations of the test results of the quartzite rock samples is presented in Table 58 of appendix 9. There are strong positive significant correlations between UCS and Young's modulus, Young's modulus and Poisson's ratio, Young's modulus and density.

Presented in appendix 9 Picture 63 shows that, obtained relationship between Young's modulus and UCS is not linear. There are distinctly two slopes on scatter plot of Young's modulus to UCS of tested quartzite rocks. One slope from 40 to70

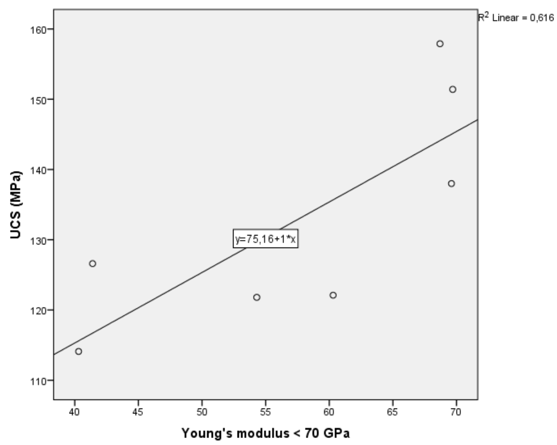
GPa and another from 70 to 90 GPa, same tendency have been noticed on analysis of granites in chapter *8.1.6*.

As can be seen in Picture 64 presented in appendix 9, considerable part of Poisson's ratio results equal to 0.1. Presented in appendix 9 Picture 65 of Density to UCS shows no linearity.

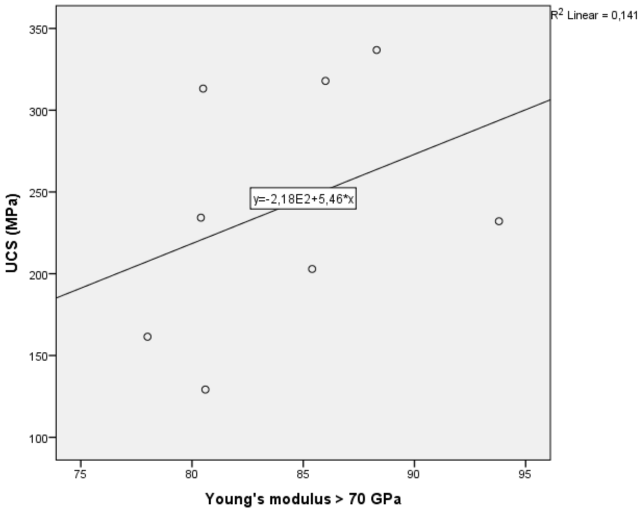
With regard to scatterplots and correlation table construction of multiple regression model could be baseless, but analysis of dependence between low/high values of Young's modulus and UCS seems to be useful.

8.10.1 Slopes of Young's modulus to UCS of tested quartzite rocks

In Pictures 66 presented scatter diagrams of Young's modulus values less than 70 GPa to uniaxial compressive strength, and in Picture 67 Young's modulus values more than 70 GPa to uniaxial compressive strength.



Picture 66. Variance of values of obtained Young's modulus from 40 to 70 GPa to UCS of tested quartzite rocks



Picture 67. Variance of values of obtained Young’s modulus from 70 to 95 GPa to UCS of tested quartzite rocks

As can be seen from Picture 66 relationship between low values of Young’s modulus and UCS is pretty strong. Although the number of observations is small. Linear regression model for low values of Young’s modulus to UCS is significant to 5 % level and R-squared value is equal to 0.616.

Linear regression model for the low values of Young’s modulus can be derived as:

$$UCS = b_0 + b_1 Young's\ modulus + \varepsilon \tag{34}$$

Model summary presented in Table 59.

Table 59: Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0,785[a]	**0,616**	0,539	11,1811

a. Predictors: (Constant) Young’s modulus

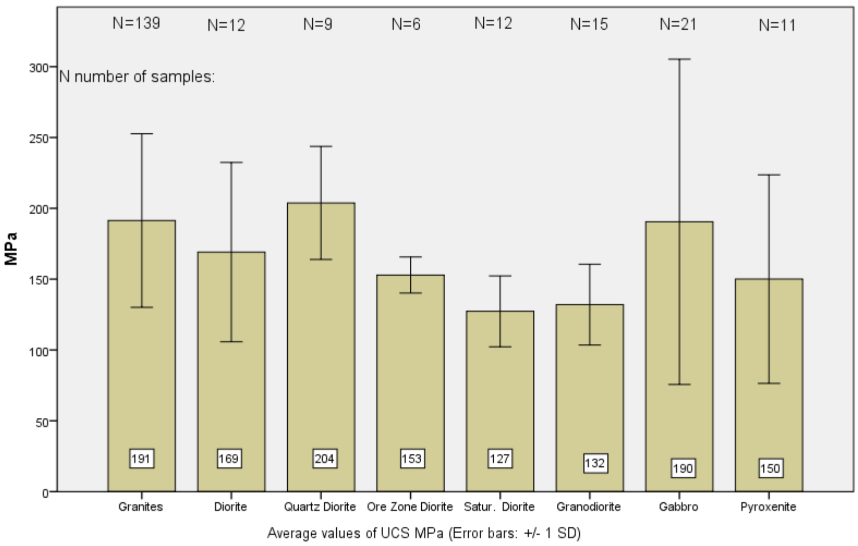
Given in appendix 9 Table 60 shows that F-value is bigger than zero and is significant to 5% level. Table 61 presented in appendix 9 shows that coefficient and intercept are significant to 5% level.

9 COMPARISON OF THE ANALYZED DATA

This chapter summarizes and compares analyzed results. Comparaisons helps to understand difference between mechanical properties of usual Finnish rocks. This chapter also presents the conclusions about the correlations between mechanical properties of different rocks that have been obtained in this thesis.

9.1 Mechanical properties of analyzed rocks

In engenering strength of materials is extreamly important, because strenght generally defines the limits of the possible. Picture 68 shows the average values of uniaxial compressive strength of the analyzed igneous rocks. As can be seen from Picture 68, the standard deviation values (error bars shows +/- 1 standard deviation) are quite high compared to the average values. This result confirms once again that UCS values of the same rocks may differ significantly, depending of the place of occurrence.



Picture 68. Average values of UCS of all analyzed igneous intrusive rocks

Obtained in this thesis observations, shows that average values of UCS of tested granite rock samples by the place of occurrence shows interval of results from 123 MPa to 265 MPa, and that is only for Espoo-Helsinki regions for 107 tested specimens. High standard deviation values explained by this great difference of obtained results of uniaxial compressive strength.

To check reliability, these results presented on picture 68 were compared to the results obtained by Pekka Patrikainen (1983) for Geological Survey of Finland. Data obtained and presented by Patrikainen may contain as well results of some Swedish rock tests referring to the study of Maa- ja vesirakennus RIL 67 (1968). A relevant fragment from data presented by Patrikainen was selected for comparison with the results in this thesis which shows the most common variations of compressive strength values of some Finnish rocks. This selected fragment is presented in table 62, as can be seen variation of the results are also appreciable. /3, 16/

Comparing the values by Patrikainen (1983) presented in table 62 with the results obtained in this thesis and presented in picture 68, a sizeable difference can be noticed. In this thesis, the obtained average value of uniaxial compression strength for granites is 4% less than the lower boundary of values by Patrikainen (1983) and presented in Table 62. Similarly, the obtained values of UCS of gabbro rocks are lower for about 27% against tha data cited by Patrikainen (1983).

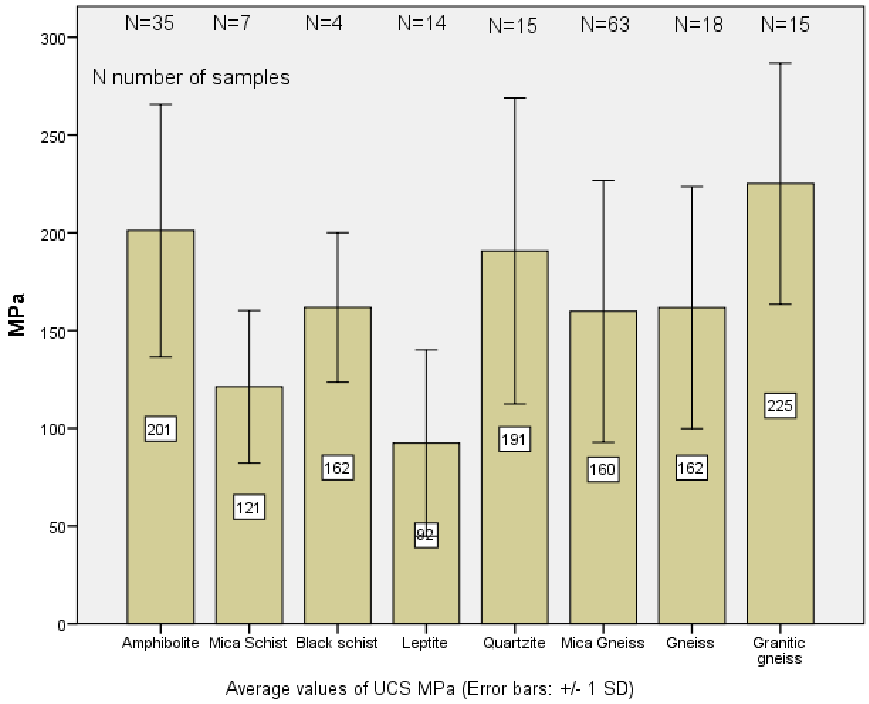
Table 62: Most common variations of compressive strength of some Finnish rocks (fragment) /3/

Rock	**UCS (MPa)**
Granite	200...350
Gneiss	150...300
Gabbro	260...350
Amphibolite	150...450
Quartzite	200...300
Mica schist	100...250
Leptite	200...450

When comparing the results obtained in this thesis on diorite rock, a considerable difference is also noticeable. It can be seen that quartz diorite has a bigger UCS value than diorite, with difference reaching to about 21%. A possible explanation for this dicrepancy is a possible lump presence of hard mineral quartz in tested quartz diorite rock samples.

Furthermore, as can be seen from Picture 68, the average UCS value of saturated diorite rocks is about 25% lower than the value for diorite rocks obtained in this thesis. This observation may indicate a direct effect of moisture on the strength.

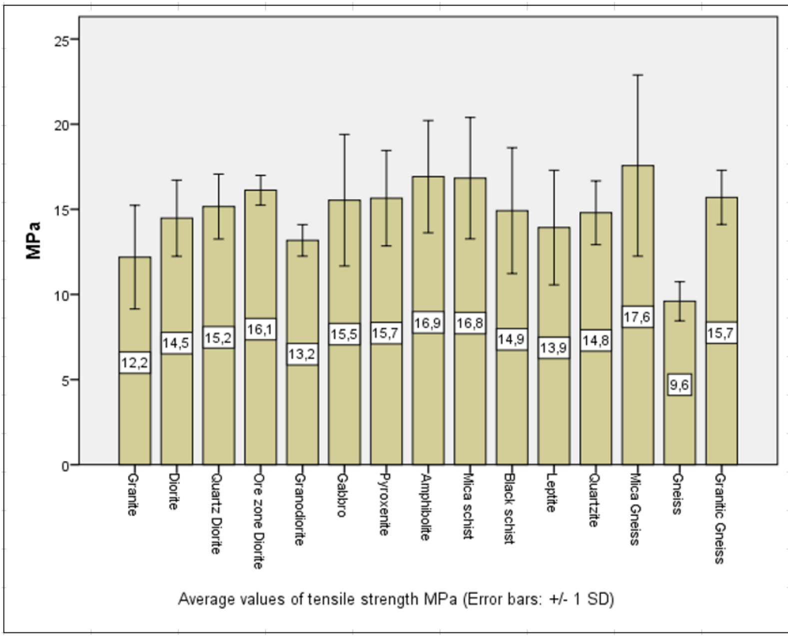
Next, the average values of UCS for all analyzed metamorphic rocks are presented in Picture 69 (as obtained in this thesis).



Picture 69. Average values of UCS of all analyzed metamorphic rocks

As can be seen from Picture 69, the standard deviation values presented by the error bar are quite high. The obtained average value of uniaxial compression strength for quartzite is 4% less than the lower boundary of values of quartzite by Patrikainen (1983) presented in Table 62. The average value of UCS of leptie rocks from this thesis (picture 69) is about 50% less than the lower boundary of interval presented in Table 62.

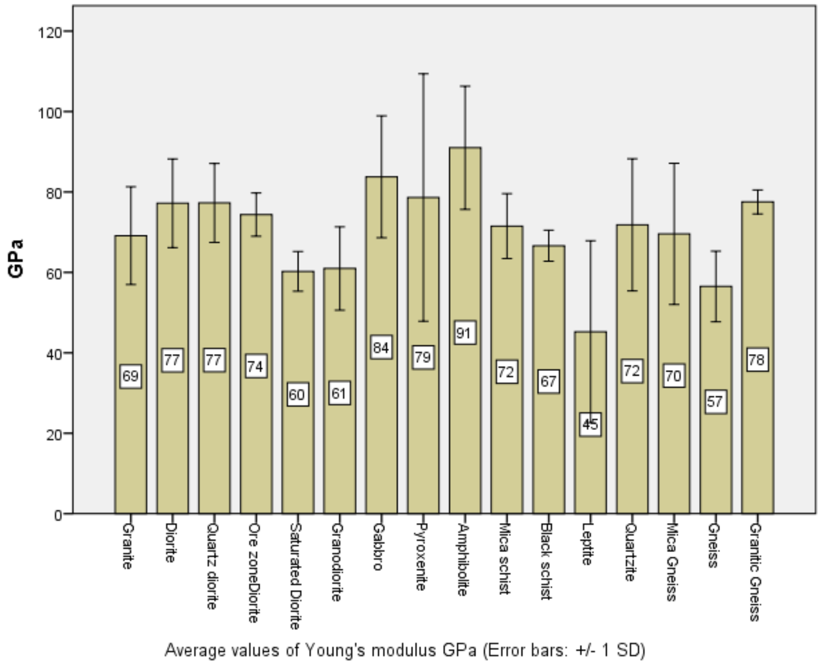
The summary of results on the average tensile strength values from the data analyzed in this thesis are collected in picture 70. As can be seen, Brazil tests were done noticeably less often than the uniaxial compressive strength tests. On average, the resuls values of tensile strength were 11 times less than uniaxial compressive strength of analyzed rocks.The average uniaxial compressive strength value of gneiss was 17 times more than average value of tensile strength. As can be seen from picture 70, gneiss demonstrate the lowest tensile strength among all other tested rocks.



Rock	N of samples
Granite	109
Diorite	9
Quartz diorite	9
Ore zone diorite	6
Granodiorite	3
Gabbro	17
Pyroxenite	5
Amphibolite	29
Mica schist	6
Black schist	4
Leptite	7
Quartzite	4
Mica Gneiss	37
Gneiss	8
Granitic gneiss	6

Picture 70. Average values of tensile strength of analyzed data

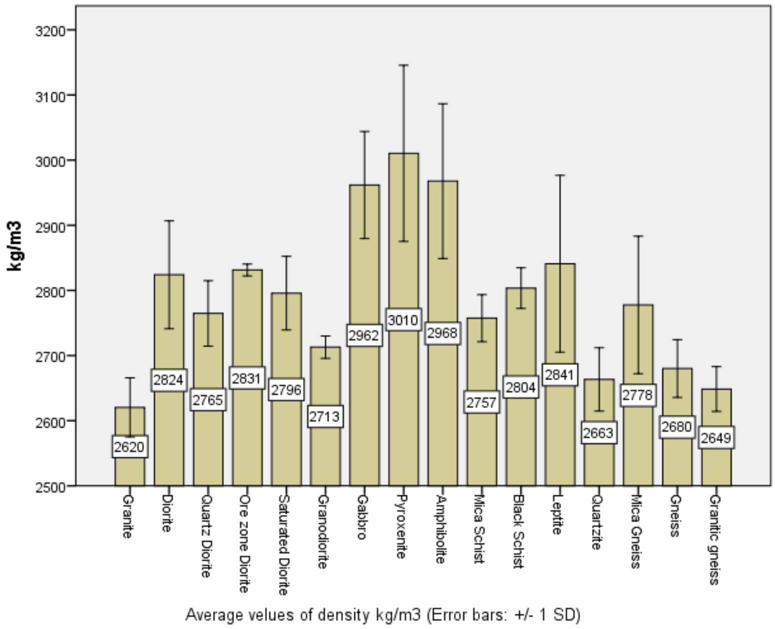
The average values of Young’s modulus of the rocks analyzed in this thesis are presented in picture 71. As can be seen, some quite high values were obtained for amphibolite and gabbro rocks in particular; and the value of standard deviation for pyroxenite is registered as extremely high. The lowest average value of Young’s modulus was measured for leptite rocks.



Picture 71. Average values of Young's modulus of tested rocks

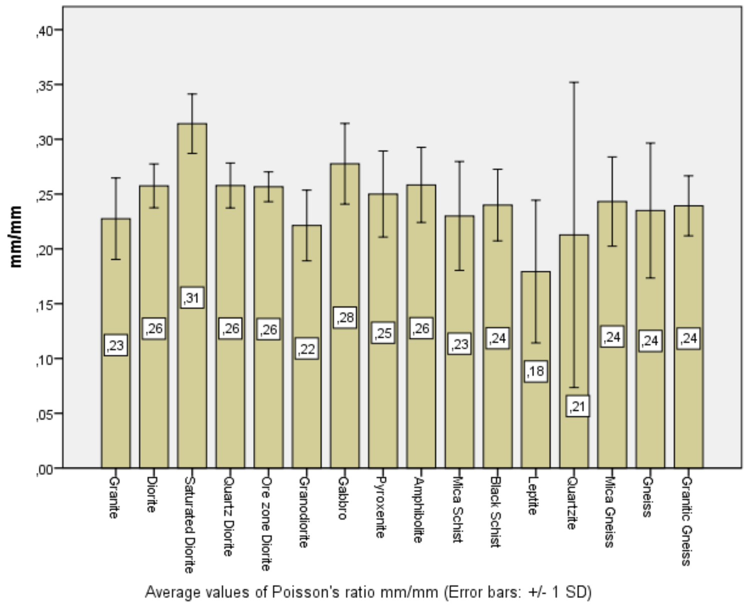
Obtained in this thesis results revealed nothing unusual for analyzed values of Young' modulus. As reported by Vuorimiesyhdistys (1982), the values of Young's modulus of Finnish rocks spread between 20–160 GPa, with the average value between 60–70 GPa. /7/

In Picture 72 the average values of densities of analyzed rocks are presented, obtained data confirmes previuos findings. According to Airo *et al.* (2013) densities of typical Finnish rocks stands between 2500–3200 kg/m^3. /17/ According to Vuorimiesyhdistys, 1982 typically density is in direct ratio to content of black minerals. /7/



Picture 72. Average values of density of tested rocks

The largest posible value of Poisson's ratio for linearly elastic material is equal to 0.5. As seen in Picture 73, the average values of Poisson's ratio of all tested rocks which were analyzed in this thesis show the typical results between 0.18-0.31.



Picture 73. Average values of Poisson's ratio of tested rocks

9.2 Correlations

After analysys and comparisons of mechanical properties of rocks, the most important was to test correlations between uniaxial compression test and Brazil test. It was significant, firstly, because it seems useful to verify how two tests that describe mechanical properties of rocks correlate to each other. Secondly, this comparison of different tests parameters is quite extensively used in rock mechanics. From the data analyzed in this thesis, significant linear correlations were obtained between UCS and tensile strength of Granites r=0.585, all gneiss rocks r=0.521, mica gneiss rocks r=0.678, Gabbro rocks r=0.778, Amphibolites r=0.439, Schist rocks r=0.622, Leptite r=0.805. Strong but not significant linear correlations were discovered between tensile strength and UCS which was measured for Pyroxene rocks r=0.676.

9.3 Regression analysis

Regression describes how strong one parameter statistically depends on some other parameter. In this thesis, the regression and multiple regression analysis were used for verification of how reliably the obtained test parameters can predict the uniaxial compressive strength. As the outcome of this analysis, several multiple linear regression models were successfully constructed for these rocks:

Granite (R-squared=0.425), regression equation:

$UCS = -63{,}359 + (9{,}972 \times Tensile) + (586{,}135 \times Poisson's\ ratio).$

Gneiss (R-squared=0.475), regression equation:

$UCS = 499{,}3 + (4{,}6 \times Tensile) + (2.6 \times Young'\ s) + (-0.21 \times Density) + \varepsilon,$

Mica gneiss (R-squared=0.760), regression equation:

$UCS = -107 + (6.7 \times Tensile) + (2.3 \times Young'\ s) + \varepsilon,$

Gabbro (R-squared=0.682), regression equation:

$UCS = -1381 + (21.5 \times Tensile) + (0{,}422 \times Density)$, and

Schist rocks (R-squared=0.561), regression equation:

$UCS = -85.3 + (4{,}84 \times Tensile) + (2{,}07 \times Young' s).$

The construction of these multiple regression models was obstruct several times due to a strong correlation between mechanical parameters, also known as the phenomenon of multicollitearity. Multicollinearity was discovered between the obtained mechanical parameters of granite, gabbro and leptire rocks.

9.4 Relationship between strength properties and grain size of rock samples

The results obtained in this thesis on the relationships of the strength properties and grain size of the tested specimens show a poor association. Therefore, the obtained results to do not allow to make any perspicacious conclusions. For granites and amphibolites, however, some relationship was noticed. The obtained results pointed to a slight reduction of the strength properties due to the increases in grain size of the specimens of granites and amphibolites.

9.5 Scatter diagrams of Young's modulus to uniaxial compressive strength

The results obtained in this thesis from scatter diagrams of Young's modulus to uniaxial compressive strenghs showed some liner relationship. In most cases, the relationship between Young's modulus and UCS shows linearity, especially when measured for gneiss, gabbro, diorite, granodiorite, pyroxenite, schist and leptite rocks. One poorly shaped scatter diagram between Young's modulus to UCS was obtained only for amphibolite rocks. The exponential spread on scatter diagram was obtained between Young's modulus and UCS for granite and quartzite rocks.

10 CONCLUSION

One of the goals of this thesis was to analyze a large group of laboratory test data collected by the Laboratory of Rock mechanics of Aalto University School of Engineering. The analysis of results confirm that the strength and mechanical properties of the Finnish rocks differ quite widely depending on the place of occurrence. High standard deviation values obtained in this thesis confirm that conclusion. If this is the case, it is very important to remember about anisotropic and inhomogeneous properties of rocks. This confirms once again the importance of careful rock mass investigation before starting any underground excavations.

Rock material is absolutely amazing by its properties, that is why samples taken from the same location or even from the same borehole may significantly differ one from another by its mechanical properties. This raises the question of how far we can go if consider rock being an elastic material.

The obtained linear correlation results have shown that for the most of analyzed rocks there was a linear dependence between uniaxial compression strength and tensile strength. In our time, these correlations and statistics are widely used in scientific work; in the future, they may be as widely applied in practical engineering tasks.

In this thesis, a big part of work concentrated on analyzing statistics and a careful, thorough description of data analysis results due to their importance as well as due to a personal interest from the researcher. The laboratory work may look tedious and time consuming to an outsider, but makes a labour of love for the reseracher who is exacting and trembling for nuances. A broken sample does not mean high quality result, the key thing is to break the specimen correctly. Rock mechanics as scientific work is fairly expensive. Extraction of samples and their preparation for accurate testing machines is fairly expensive. Statistical information and observation records could make it possible to use more inexpensive tests results to predict possible values of more expensive tests.

The obtained results of linear correlation values are significant, which makes it reasonable to continue with further observations on this topic. With a properly initial classification of the test results, this kind of analysis could be superficially carried by software.

The main challenge encountered when working on this thesis was a large amount of information which exceeded any possibility to effectively present it in a limited format of a thesis study. Therefore, it is possible that similar analysis may be better conducted if done for only one specific rock, or if studying one particular property of the rock as its focus. For example, an analysis of dependence of strength properties on the grain size of specimens can make an interesting and productive study, since the results obtained in this thesis have proven this analysis to be challening and useful, and this requires further research in the field.

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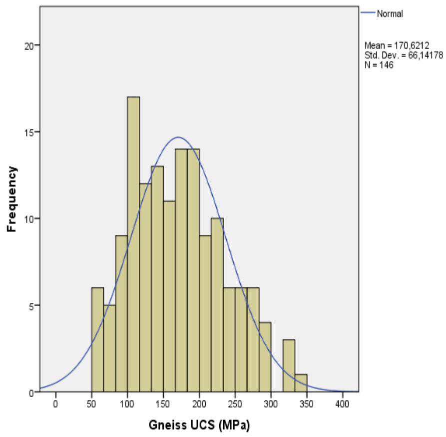
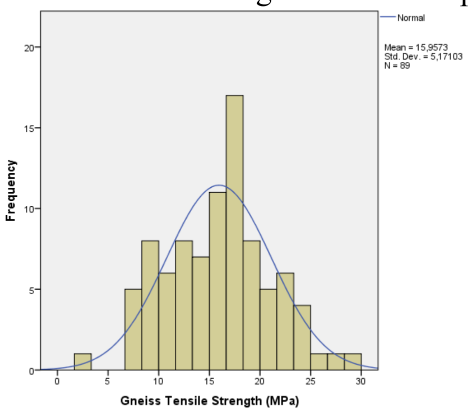
Appendix

List of appendices

Appendix 1. Gneiss



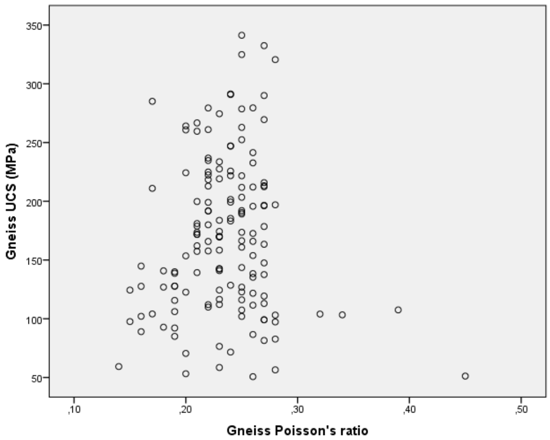
Picture 23. Histogram for the UCS of the gneiss rock samples



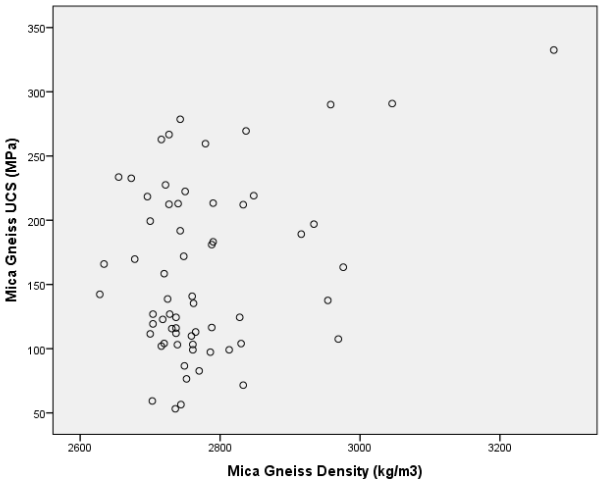
Picture 24. Histogram of Tensile strength of gneiss in total of 89 tests

Table 20: Gneiss Correlations

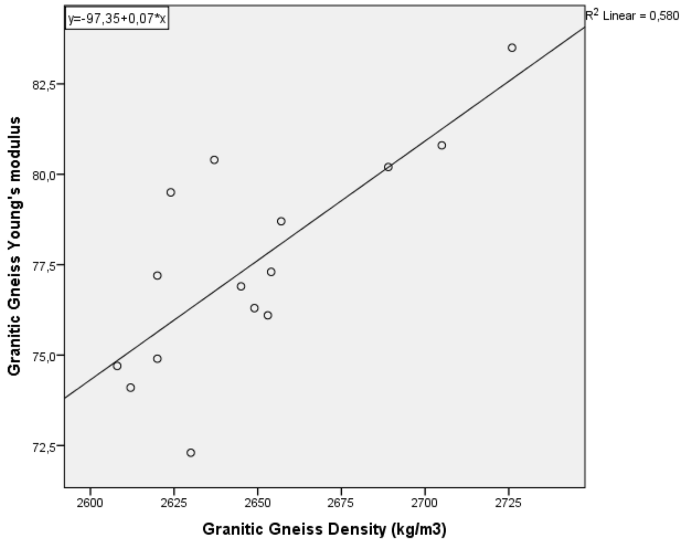
		UCS (MPa)	Tensile Strength (MPa)	Young's modu-lus (GPa)	Poisson's ratio	Density (kg/m3)	Grain Size (mm)
UCS (MPa)	Pearson Correlation	1,0	**0,521****	**0,581****	0,018	0,001	-0,071
	Sig. (2-tailed)		**0,000**	**0,000**	0,826	0,986	0,598
	N	146	89	146	146	146	57
Tensile Str (MPa)	Pearson Correlation	**0,521****	1,0	**0,429****	0,213*	0,2	-0,3
	Sig. (2-tailed)	**0,000**		**0,000**	0,045	0,080	0,074
	N	89	89	89	89	89	45
Young's modulus (GPa)	Pearson Correlation	**0,581****	**0,429****	1,0	0,1	**0,473****	0,0
	Sig. (2-tailed)	**0,000**	**0,000**		0,351	**0,000**	0,765
	N	146	89	146	146	146	57
Poisson's ratio	Pearson Correlation	0,018	0,213*	0,1	1,0	0,211*	0,0
	Sig. (2-tailed)	0,826	0,045	0,351		0,011	0,987
	N	146	89	146	146	146	57
Density (kg/m3)	Pearson Correlation	0,0014	0,187	**0,473****	0,211*	1,0	-0,16
	Sig. (2-tailed)	0,986	0,080	0,000	0,011		0,227
	N	146	89	146	146	146	57
Average Grain Size (mm)	Pearson Correlation	-0,071	-0,269	0,040	-0,002	-0,163	1,000
	Sig. (2-tailed)	0,598	0,074	0,765	0,987	0,227	
	N	57	45	57	57	57	57
**. Correlation is significant at the 0.01 level (2-tailed).							
*. Correlation is significant at the 0.05 level (2-tailed).							



Picture 27. Scatter plot of tested Gneiss Poisson's ratio to UCS



Picture 30. scatter plot of Density to UCS of tested mica gneiss samples



Picture 31. Scatter plot density to Young's modulus of tested granitic gneiss samples

Table 22:ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	197461,947	3	65820,649	**25,667**	**0,000**[b]
	Residual	217977,117	85	2564,437		
	Total	415439,064	88			

a. Dependent Variable: UCS

b. Predictors: (Constant), Density, Tensile Strength, Young's modulus

Table 23:Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	499,275	133,335		**3,745**	**0,000**
	Tensile strength (MPa)	4,596	1,157	0,346	**3,972**	**0,000**
	Young's modulus (GPa)	2,559	0,456	0,568	**5,613**	**0,000**
	Density (kg/m3)	-0,209	0,053	-0,367	**-3,942**	**0,000**

a. Dependent Variable: UCS

Table 24: Correlations between parameters of tested mica gneiss rocks

		UCS (MPa)	Tensile Str (MPa)	Young's modulus (GPa)	Poisson's ratio	Density (kg/m3)
UCS (MPa)	Pearson Correlation	1	**0,678****	**0,798****	-0,006	0,335**
	Sig. (2-tailed)		**0,000**	**0,000**	0,960	0,007
	N	63	37	63	63	63
Tensile Str (MPa)	Pearson Correlation	**0,678****	1	0,268	0,155	0,163
	Sig. (2-tailed)	**0,000**		0,108	0,360	0,334
	N	37	37	37	37	37
Young's modulus (GPa)	Pearson Correlation	**0,798****	0,268	1	0,105	**0,544****
	Sig. (2-tailed)	**0,000**	0,108		0,412	**0,000**
	N	63	37	63	63	63
Poisson's ratio	Pearson Correlation	-0,006	0,155	0,105	1	,349**
	Sig. (2-tailed)	0,960	0,360	0,412		0,005
	N	63	37	63	63	63
Density (kg/m3)	Pearson Correlation	0,335**	0,163	**0,544****	,349**	1
	Sig. (2-tailed)	0,007	0,334	0,000	0,005	
	N	63	37	63	63	63

**. Correlation is significant at the 0.01 level (2-tailed).

Table 26: ANOVA [a] (mica gneiss rocks)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	124602,505	2	62301,252	**53,848**	**0,000[b]**
	Residual	39337,226	34	1156,977		
	Total	163939,730	36			

a. Dependent Variable: UCS

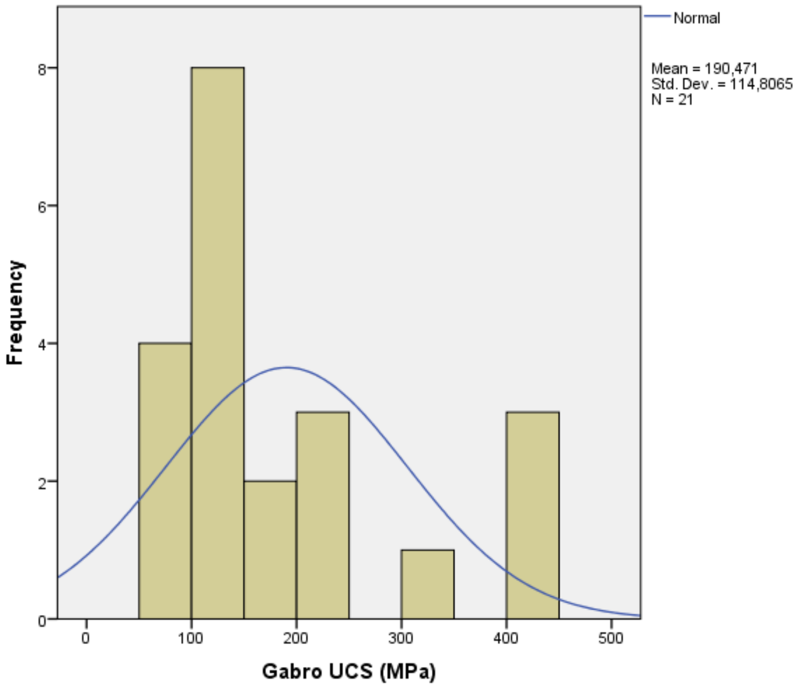
b. Predictors: (Constant), Young's modulus, Tensile strength

Table 27:Coefficients[a] (mica gneiss rocks)

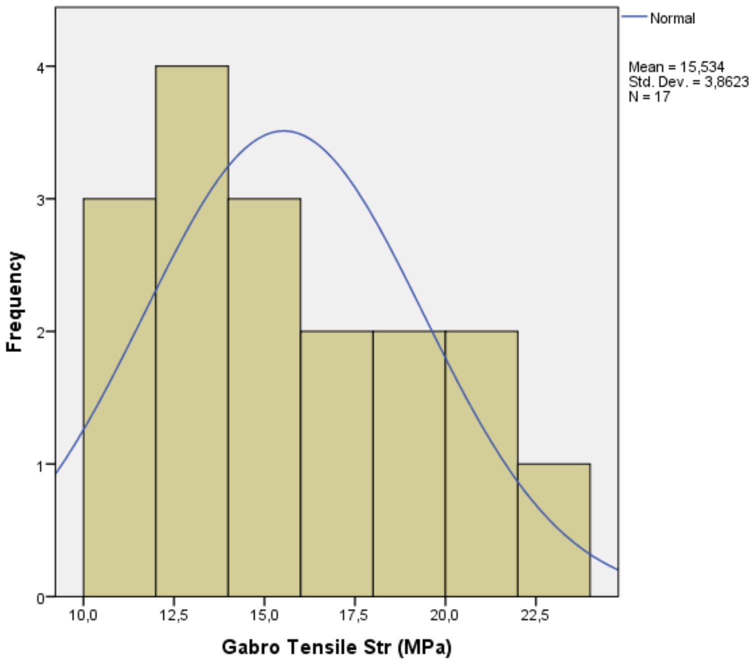
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-106,810	30,041		-3,555	0,001
	Tensile strength	6,667	1,106	0,526	6,030	0,000
	Young's modulus	2,336	,358	0,568	6,518	0,000

a. Dependent Variable: UCS

Appendix 2. Gabbro



Picture 33. Histogram for the UCS of the gabbro rock samples



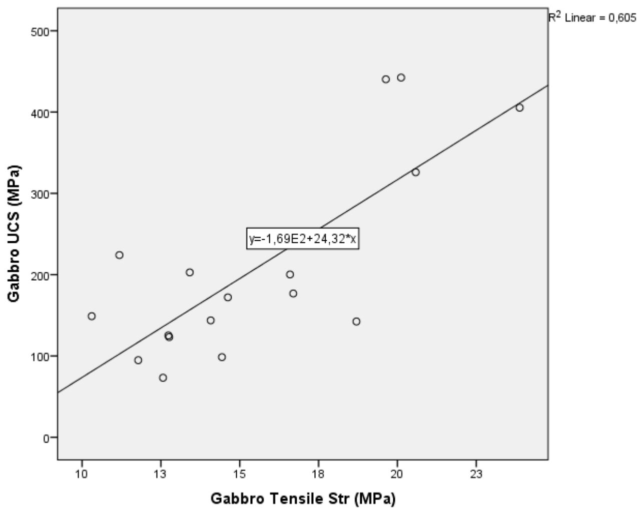
Picture 34. Histogram of Tensile strength of gabbro rocks in total of 17 tests

Tabel 29: Correlations Gabbro rocks

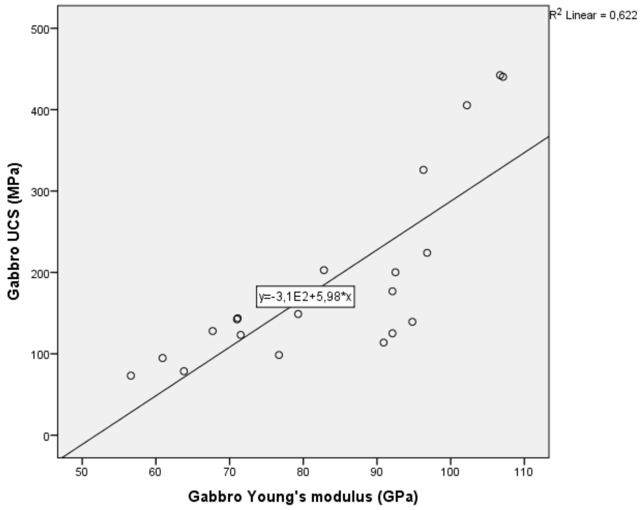
		UCS (MPa)	Tensile (MPa)	Young's modulus (Gpa)	Poisson's ratio	Density (kg/m3)
UCS (MPa)	Pearson Correlation	1	**0,778****	**0,789****	0,24	**0,512***
	Sig. (2-tailed)		0,000	0,000	0,29	0,018
	N	21	17	21	21	21
Tensile (MPa)	Pearson Correlation	**0,778****	1	**0,599***	0,25	0,31
	Sig. (2-tailed)	0,000		0,01	0,34	0,23
	N	17	17	17	17	17
Young's modulus (Gpa)	Pearson Correlation	**0,789****	**0,599***	1	-0,10	**0,622****
	Sig. (2-tailed)	0,00	0,01		0,67	0,00
	N	21	17	21	21	21
Poisson's ratio	Pearson Correlation	0,24	0,25	-,099	1,00	-0,30
	Sig. (2-tailed)	0,29	0,34	0,67		0,18
	N	21	17	21	21	21
Density (kg/m3)	Pearson Correlation	**0,512***	0,31	**0,622****	-0,30	1
	Sig. (2-tailed)	0,02	0,23	0,00	0,18	
	N	21	17	21	21	21

**. Correlation is significant at the 0.01 level (2-tailed).

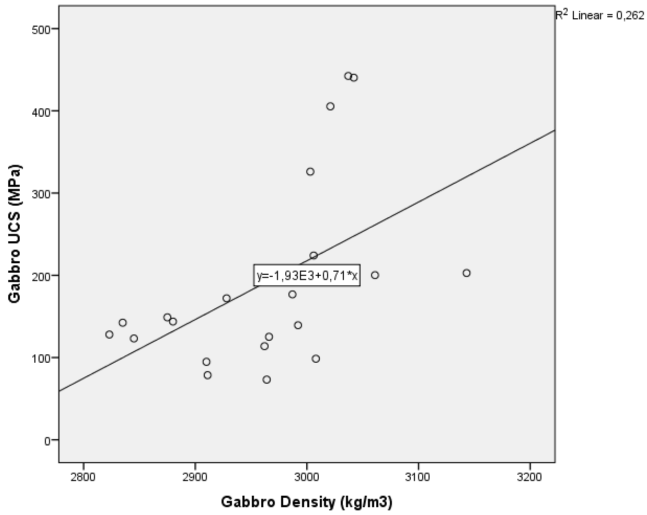
*. Correlation is significant at the 0.05 level (2-tailed).



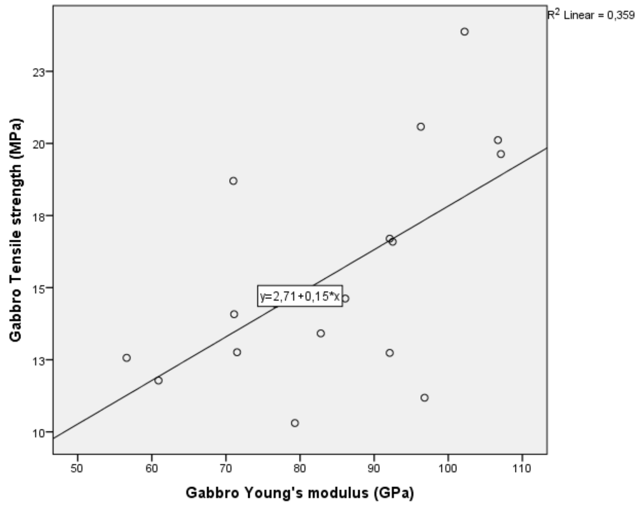
Picture 35. Scatterplot of Tensile strength to UCS of tested gabbro rocks



Picture 36. Scatterplot of Young's modulus to tensile strength of tested gabbro rocks



Picture 37. Scatterplot of density to UCS of tested gabbro rocks



Picture 38. Scatterplot of Young's modulus to tensile strength of tested gabbro rocks

Table 31: ANOVA[a] (Gabbro)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	159059,075	2	79529,537	**14,992**	**0,000[b]**
	Residual	74264,968	14	5304,641		
	Total	233324,042	16			

a. Dependent Variable:UCS

b. Predictors: (Constant), Density, Tensile

Table 32: Coefficients

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-1380,976	663,391		-2,082	**0,056**
	Tensile	21,513	4,955	0,688	4,342	0,001
	Density	0,422	,230	0,291	1,838	**0,087**

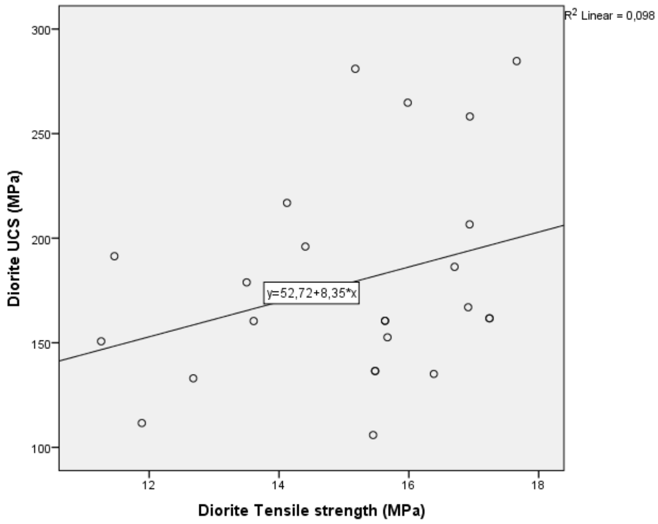
a. Dependent Variable: UCS

Appendix 3. Diorite

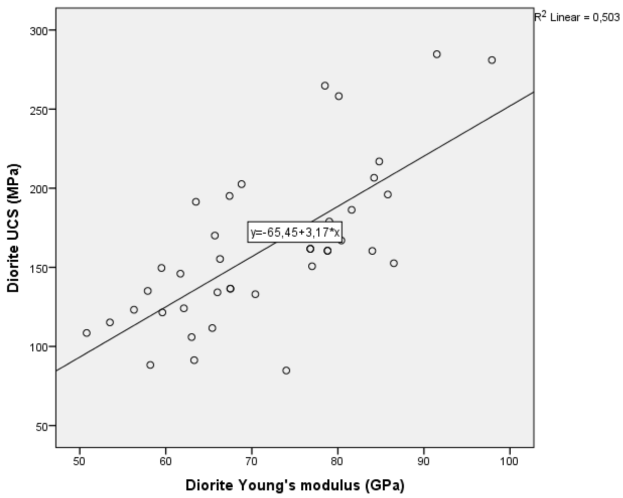
Table 38: Correlations Diorite

		UCS (MPa)	Tensile (MPa)	Young's modulus (Gpa)	Poisson's ratio	Density (kg/m3)
UCS (MPa)	Pearson Correlation	1	0,313	**0,710****	-0,271	-0,083
	Sig. (2-tailed)		0,137	**0,000**	,095	0,615
	N	39	24	39	39	39
Tensile (MPa)	Pearson Correlation	0,31	1	0,28	-,055	0,182
	Sig. (2-tailed)	0,14		0,19	0,797	0,396
	N	24	24	24	24	24
Young's modulus (Gpa)	Pearson Correlation	**0,710****	0,279	1	**-0,618****	0,273
	Sig. (2-tailed)	0,000	0,187		**0,000**	0,093
	N	39	24	39	39	39
Poisson's ratio	Pearson Correlation	-0,27	-0,055	-0,618**	1	0,037
	Sig. (2-tailed)	0,10	0,797	0,00		0,822
	N	39	24	39	39	39
Density (kg/m3)	Pearson Correlation	-0,08	0,182	0,27	0,037	1
	Sig. (2-tailed)	0,61	0,396	0,09	0,822	
	N	39	24	39	39	39

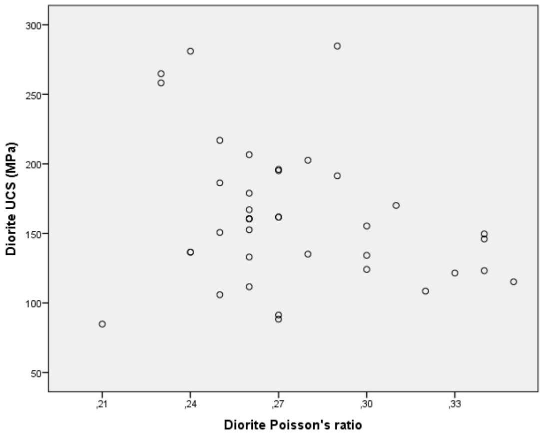
**. Correlation is significant at the 0.01 level (2-tailed).



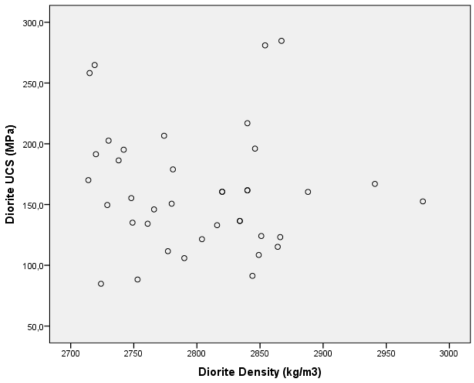
Picture 39. Scatterplot of Tensile strength to UCS of tested diorite rock samples



Picture 40. Scatterplot of Young’s modulus to UCS of tested diorite rocks



Picture 41. Scatter plot of Poisson’s ratio to UCS of tested diorite rocks



Picture 42. Scatter plot of Density to UCS of tested diorite rocks

Table 40: ANOVA[a] (Diorite)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	29605,120	2	14802,560	**10,678**	**0,001[b]**
	Residual	29112,589	21	1386,314		
	Total	58717,710	23			

a. Dependent Variable: Diorite UCS

b. Predictors: (Constant), Diorite Young’s modulus, Diorite Tensile strength

Table 41: Coefficients[a] (Diorite)

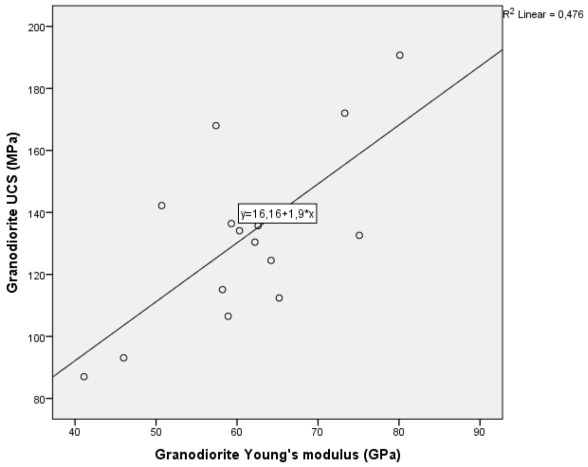
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-142,260	78,258		-1,818	**0,083**
	Tensile strength	3,402	4,271	0,127	0,796	**0,435**
	Young’s modulus	3,486	0,840	0,664	4,149	0,000

a. Dependent Variable:UCS

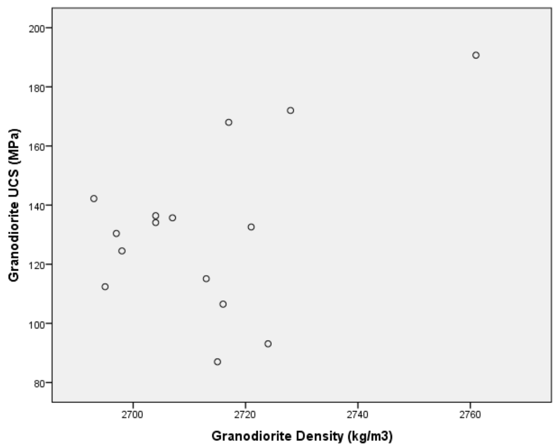
Appendix 4. Granodiorite

Table 43: Correlations Granodiorite

		UCS (MPa)	Tensile (MPa)	Young's modulus (Gpa)	Poisson's ratio	Density (kg/m3)
UCS (MPa)	Pearson Correlation	1	**-0,833**	**0,690****	0,212	0,462
	Sig. (2-tailed)		**0,373**	0,004	0,448	0,083
	N	15	3	15	15	15
Tensile (MPa)	Pearson Correlation	**-0,833**	1	0,000	-0,967	-0,411
	Sig. (2-tailed)	**0,373**		1,000	0,165	0,730
	N	3	3	3	3	3
Young's modulus (Gpa)	Pearson Correlation	**0,690****	0,000	1	,668**	0,426
	Sig. (2-tailed)	**0,004**	1,000		0,006	0,113
	N	15	3	15	15	15
Poisson's ratio	Pearson Correlation	0,21	-0,967	0,668**	1	0,017
	Sig. (2-tailed)	0,45	0,165	0,006		0,952
	N	15	3	15	15	15
Density (kg/m3)	Pearson Correlation	0,46	-0,411	0,426	0,017	1
	Sig. (2-tailed)	0,08	0,730	0,113	0,952	
	N	15	3	15	15	15
**. Correlation is significant at the 0.01 level (2-tailed).						

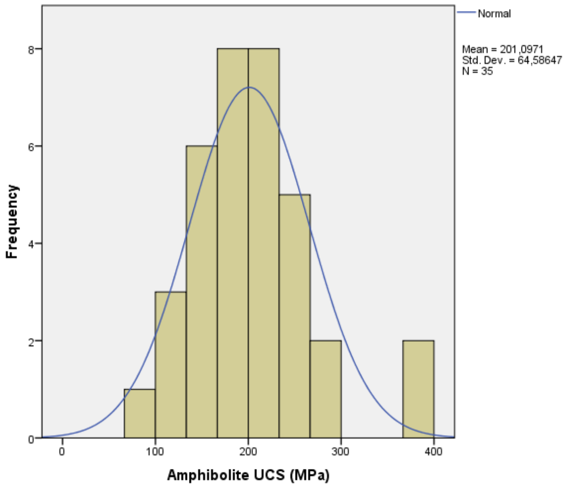


Picture 43: Scatterplot of Young's modulus to UCS of tested granodiorite rocks

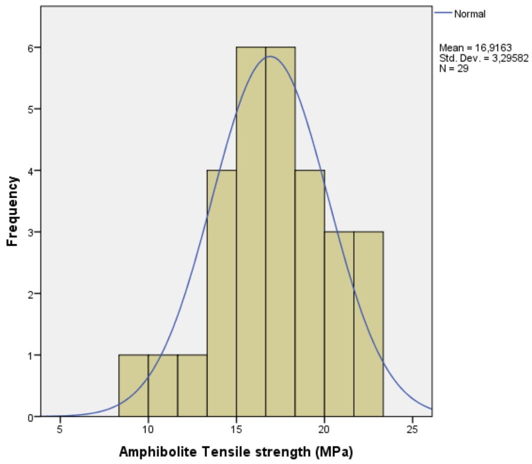


Picture 44. Scatterplot of Density to UCS of tested granodiorite rocks

Appendix 5. Amphibolite



Picture 45. Spread of UCS of tested amphibolite rocks.



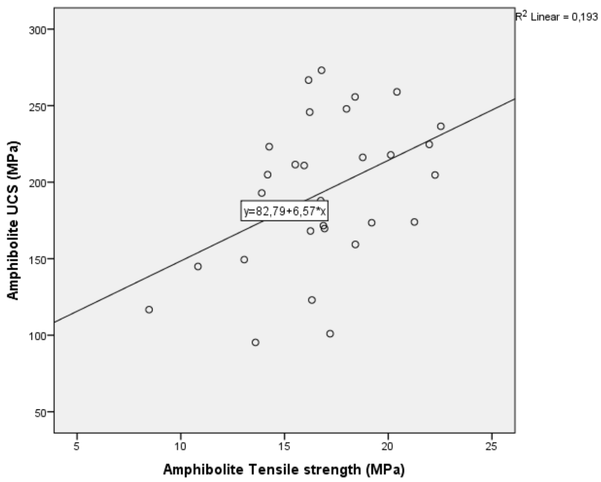
Picture 46. Histogram of tested for Tensile strength amphibolite rock samples

Table 45:Correlations of tested parameters of amphibolite rocks samples

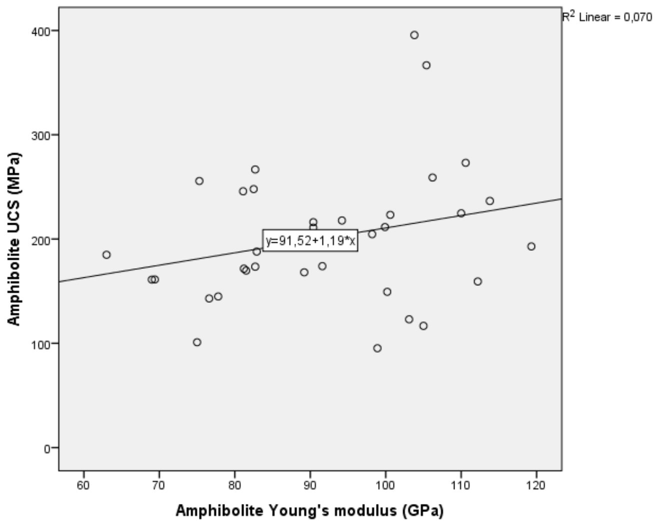
		UCS (MPa)	Tensile (MPa)	Young's modulus (Gpa)	Poisson's ratio	Density (kg/m3)	Grain size (mm)
UCS (MPa)	Pearson Correlation	1	**0,439***	0,265	0,270	-0,026	-0,093
	Sig. (2-tailed)		**0,017**	0,124	0,117	0,881	0,751
	N	35	29	35	35	35	14
Tensile (MPa)	Pearson Correlation	**0,439***	1	0,066	0,265	0,155	-0,343
	Sig. (2-tailed)	**0,017**		0,735	0,166	0,423	0,230
	N	29	29	29	29	29	14
Young's modulus (Gpa)	Pearson Correlation	0,26	0,07	1	-0,037	**0,634****	-0,043
	Sig. (2-tailed)	0,12	0,74		0,829	**0,000**	0,883
	N	35	29	36	36	36	14
Poisson's ratio	Pearson Correlation	0,27	0,26	-0,037	1	0,128	-0,066
	Sig. (2-tailed)	0,12	0,17	0,829		0,457	0,823
	N	35	29	36	36	36	14
Density (kg/m3)	Pearson Correlation	-0,03	0,15	**0,634****	0,128	1	0,249
	Sig. (2-tailed)	0,88	0,42	**0,000**	0,457		0,390
	N	35	29	36	36	36	14
Grain size (mm)	Pearson Correlation	-0,09	-0,34	-0,043	-0,066	0,249	1
	Sig. (2-tailed)	0,75	0,23	0,883	0,823	0,390	
	N	14	14	14	14	14	14

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).



Picture 47. Scatterplot of tensile strength to UCS of tested amphibolite rocks



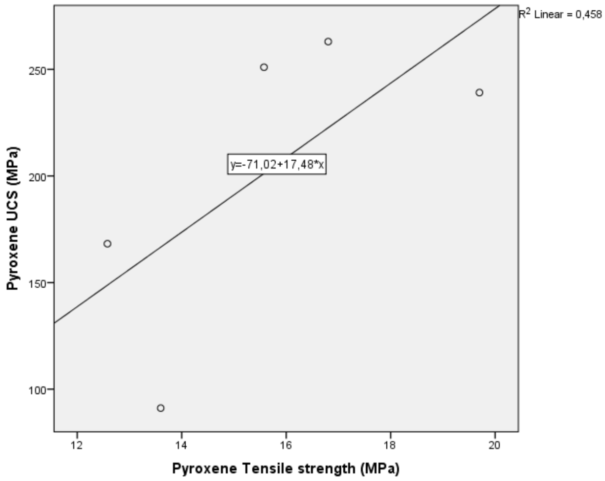
Picture 48. Scatterplot of Young’s modulus to UCS of tested amphibolite rocks

Appendix 6. Pyroxenite

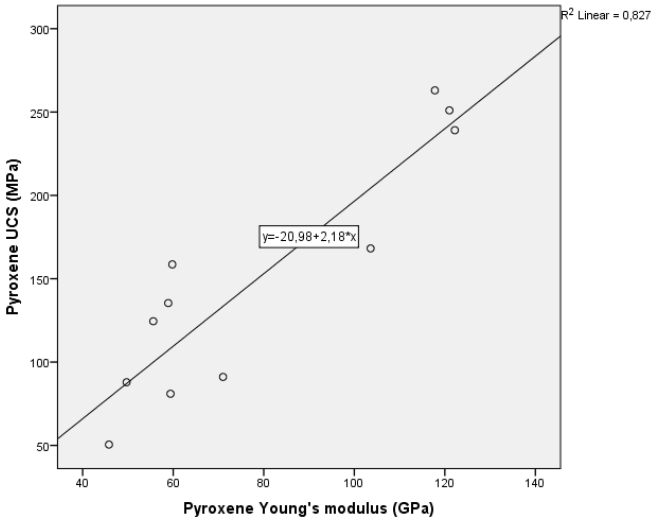
Table 47:Correlations

		UCS (MPa)	Tensile (MPa)	Young's modulus (Gpa)	Poisson's ratio	Density (kg/m3)
UCS (MPa)	Pearson Correlation	1	0,676	**0,909****	0,230	**0,878****
	Sig. (2-tailed)		0,210	**0,000**	0,496	**0,000**
	N	11	5	11	11	11
Tensile Strenght (MPa)	Pearson Correlation	0,676	1	0,653	-0,348	0,554
	Sig. (2-tailed)	0,210		0,233	0,566	0,332
	N	5	5	5	5	5
Young's modulus (Gpa)	Pearson Correlation	**0,909****	0,653	1	0,124	**0,800****
	Sig. (2-tailed)	**0,000**	0,233		0,717	**0,003**
	N	11	5	11	11	11
Poisson's ratio	Pearson Correlation	0,230	-0,348	0,124	1	0,257
	Sig. (2-tailed)	0,496	0,566	0,717		0,446
	N	11	5	11	11	11
Density (kg/m3)	Pearson Correlation	**0,878****	0,554	**0,800****	0,257	1
	Sig. (2-tailed)	**0,000**	0,332	**0,003**	0,446	
	N	11	5	11	11	11

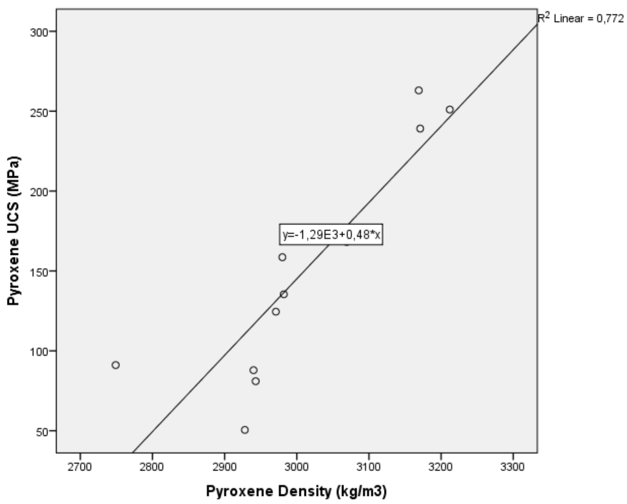
**. Correlation is significant at the 0.01 level (2-tailed).



Picture 50. Scatter plot of tensile strength to UCS of tested Pyroxenite rocks



Picture 51. Scatter plot of Young's modulus to UCS of tested pyroxenite rocks.



Picture 52. Scatterplot of density to UCS

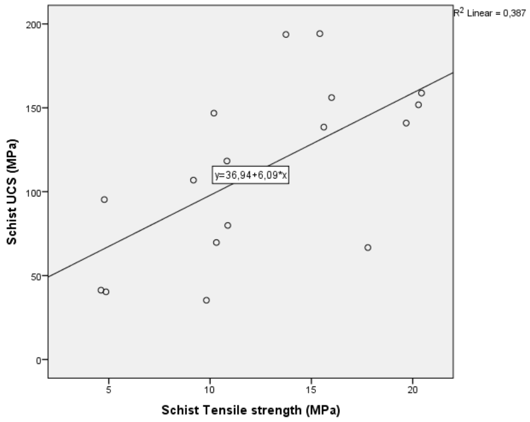
Appendix 7. Schist

Table 51: Correlations

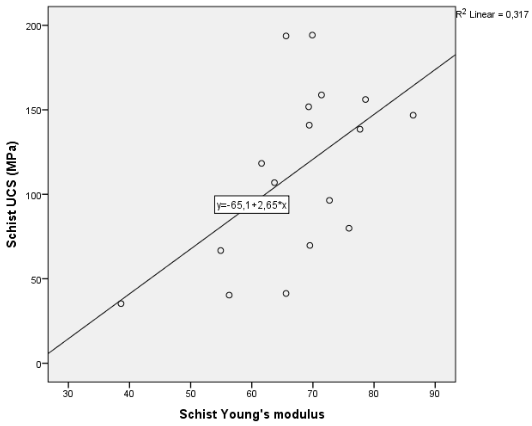
		UCS (MPa)	Tensile (MPa)	Young's modulus (Gpa)	Poisson's ratio	Density (kg/m3)
UCS (MPa)	Pearson Correlation	1	**0,622****	**0,563***	**0,646****	-0,218
	Sig. (2-tailed)		**0,008**	**0,015**	**0,004**	0,385
	N	18	17	18	18	18
Tensile (MPa)	Pearson Correlation	**0,622****	1	0,292	**0,626****	-0,047
	Sig. (2-tailed)	**0,008**		0,256	**0,007**	0,859
	N	17	17	17	17	17
Young's modulus (Gpa)	Pearson Correlation	**0,563***	0,292	1	0,392	-0,158
	Sig. (2-tailed)	**0,015**	0,256		0,107	0,533
	N	18	17	18	18	18
Poisson's ratio	Pearson Correlation	**0,646****	**0,626****	0,392	1	-0,125
	Sig. (2-tailed)	**0,004**	**0,007**	0,107		0,620
	N	18	17	18	18	18
Density (kg/m3)	Pearson Correlation	-0,218	-0,047	-0,158	-0,125	1
	Sig. (2-tailed)	0,385	0,859	0,533	0,620	
	N	18	17	18	18	18

**. Correlation is significant at the 0.01 level (2-tailed).

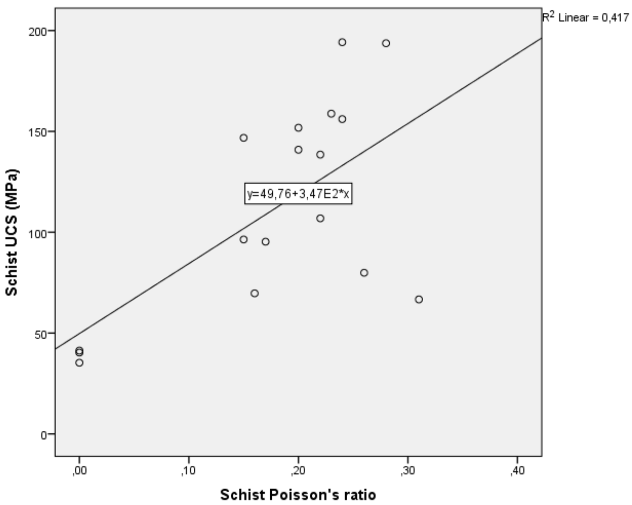
*. Correlation is significant at the 0.05 level (2-tailed).



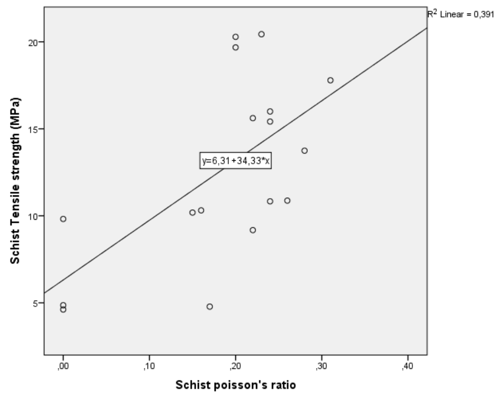
Picture 53. Scatter plot of tensile strength to UCS of tested schist rocks



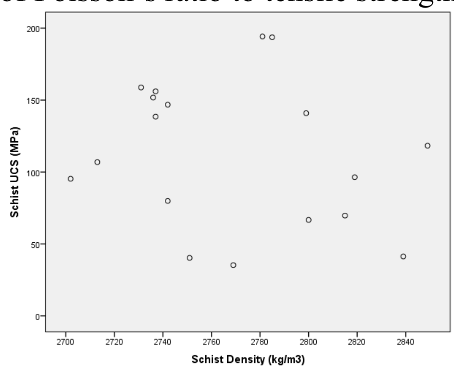
Picture 54. Scatter plot of Young’s modulus to UCS of tested schist rocks



Picture 55. Scatter plot of Poisson’s ratio to UCS of tested schist rocks



Picture 56. Scatter plot of Poisson’s ratio to tensile strength of tested schist rocks



Picture 57. Scatter plot of Density to UCS of tested schist rocks

Table 53:ANOVA[a] (schist)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	24179,922	2	12089,961	**8,954**	**0,003[b]**
	Residual	18903,327	14	1350,238		
	Total	43083,249	16			

a. Dependent Variable: UCS

b. Predictors: (Constant), Young’s modulus, Tensile strength

Table 54:Coefficients[a] (schist)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-85,335	56,945		-1,499	0,156
	Tensile strength	4,844	1,814	0,494	2,671	**0,018**
	Young’s modulus	2,070	0,877	0,437	2,360	**0,033**

a. Dependent Variable: UCS

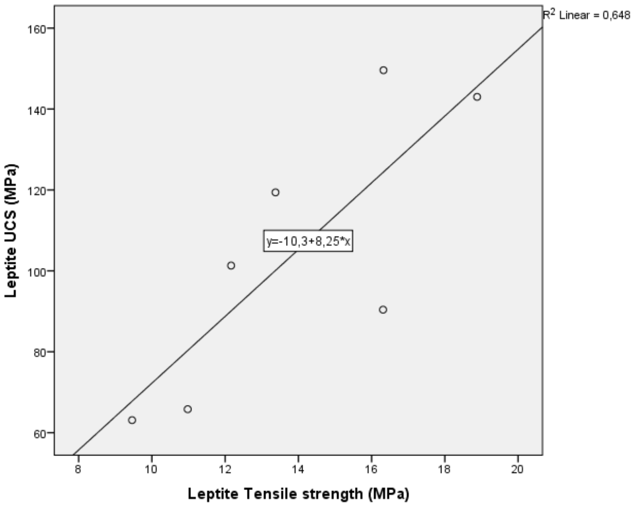
Appendix 8. Leptite

Table 56: Linear correlations leptite

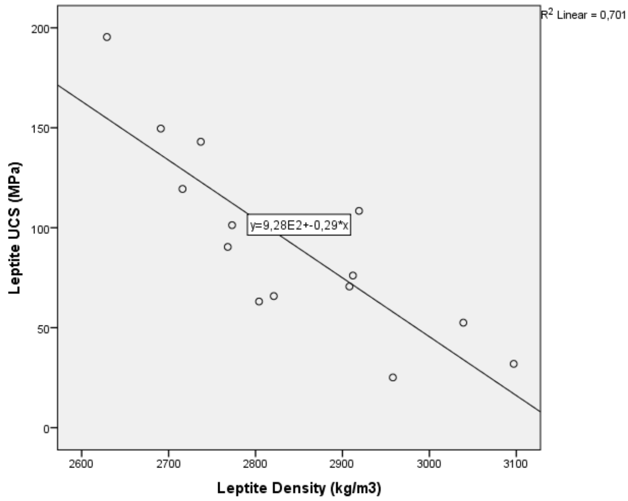
		UCS (MPa)	Tensile (MPa)	Young's modulus (Gpa)	Poisson's ratio	Density (kg/m3)
UCS (MPa)	Pearson Correlation	1	**0,805***	**0,868****	**0,708****	**-0,837****
	Sig. (2-tailed)		**0,029**	**0,000**	**0,005**	**0,000**
	N	14	7	14	14	14
Tensile (MPa)	Pearson Correlation	**0,805***	1	**0,710**	0,499	-0,673
	Sig. (2-tailed)	**0,029**		**0,074**	0,254	0,098
	N	7	7	7	7	7
Young's modulus (Gpa)	Pearson Correlation	**0,868****	0,710	1	**0,841****	**-0,849****
	Sig. (2-tailed)	**0,000**	0,074		**0,000**	**0,000**
	N	14	7	14	14	14
Poisson's ratio	Pearson Correlation	**0,708****	0,499	**0,841****	1	**-0,846****
	Sig. (2-tailed)	**0,005**	0,254	**0,000**		**0,000**
	N	14	7	14	14	14
Density (kg/m3)	Pearson Correlation	**-0,837****	-0,673	**-0,849****	**-0,846****	1
	Sig. (2-tailed)	**0,000**	0,098	**0,000**	**0,000**	
	N	14	7	14	14	14

*. Correlation is significant at the 0.05 level (2-tailed).

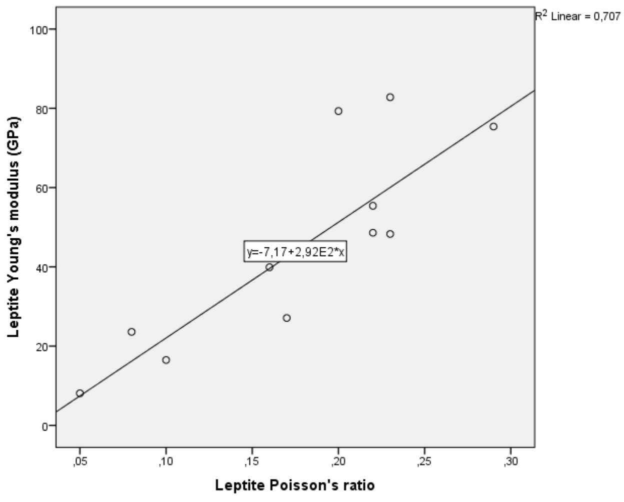
**. Correlation is significant at the 0.01 level (2-tailed).



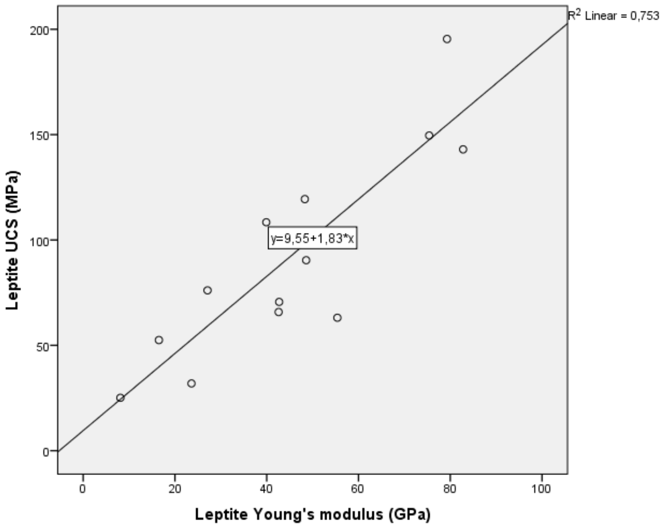
Picture 58. Scatter plot of tensile strength to UCS of tested leptite rocks



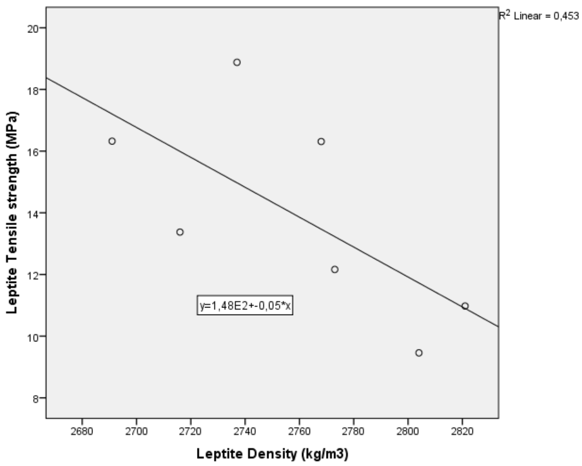
Picture 59. Scatterplot of density to UCS of tested leptite rocks



Picture 60. Scatterplot of Poisson’s ratio to Yong’s modulus of tested leptite rocks



Picture 61. Scatterplot of Yong’s modulus to UCS of tested leptite rocks



Picture 62. Scatterplot of density to Tensile strength of tested leptite rocks

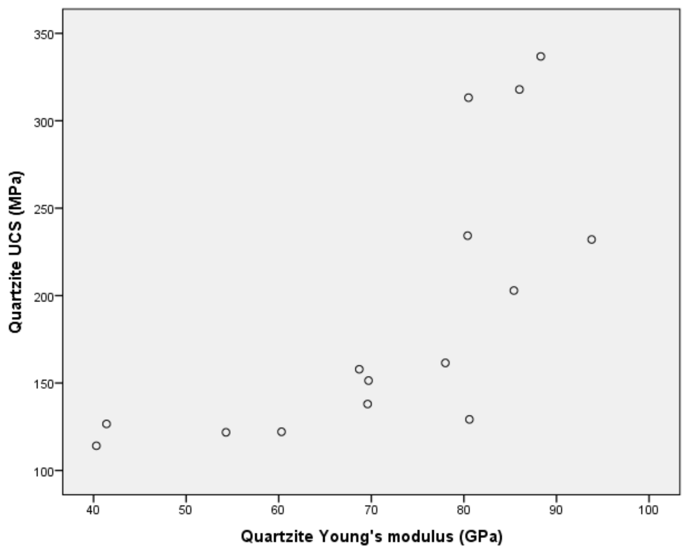
Appendix 9. Quartzite

Table 58: Correlations (quartzite)

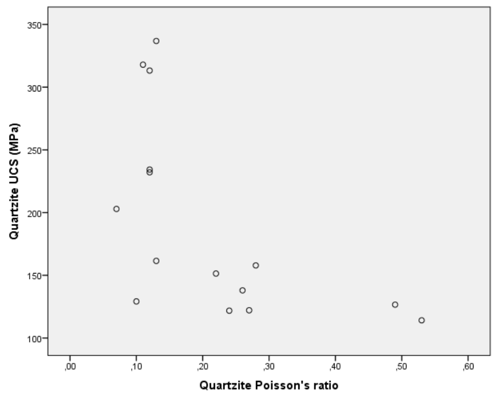
		UCS (MPa)	Tensile (MPa)	Young's modulus (Gpa)	Poisson's ratio	Density (kg/m3)
UCS (MPa)	Pearson Correlation	1	0,477	**0,703****	**-0,588***	0,341
	Sig. (2-tailed)		0,523	**0,003**	**0,021**	0,214
	N	15	4	15	15	15
Tensile (MPa)	Pearson Correlation	0,477	1	0,750	-0,113	0,348
	Sig. (2-tailed)	0,523		0,250	0,887	0,652
	N	4	4	4	4	4
Young's modulus (Gpa)	Pearson Correlation	0,703**	0,750	1	**-0,930****	**0,750****
	Sig. (2-tailed)	0,003	0,250		**0,000**	**0,001**
	N	15	4	15	15	15
Poisson's ratio	Pearson Correlation	**-0,588***	-0,113	**-0,930****	1	**-0,616***
	Sig. (2-tailed)	**0,021**	0,887	**0,000**		**0,014**
	N	15	4	15	15	15
Density (kg/m3)	Pearson Correlation	0,341	0,348	**0,750****	**-0,616***	1
	Sig. (2-tailed)	0,214	0,652	**0,001**	**0,014**	
	N	15	4	15	15	15

**. Correlation is significant at the 0.01 level (2-tailed).

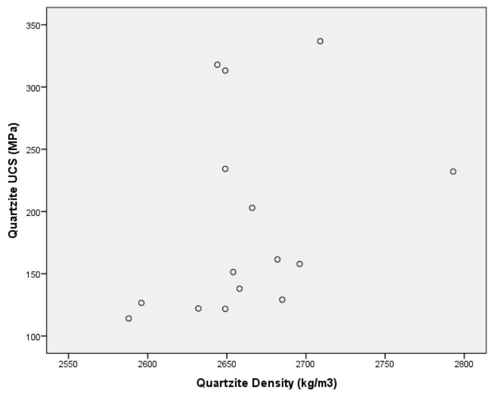
*. Correlation is significant at the 0.05 level (2-tailed).



Picture 63. Scatter plot Young’s modulus to UCS of tested quartzite rocks



Picture 64. Scatterplot of Poisson’s ratio to UCS of tested quartzite rock samples



Picture 65. Scatterplot of Density to UCS of tested quartzite samples.

Table 60:ANOVA[a] (Quartzite)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1000,794	1	1000,794	**8,005**	**0,037[b]**
	Residual	625,080	5	125,016		
	Total	1625,874	6			

a. Dependent Variable: UCS

b. Predictors: (Constant), Young’s modulus

Table 61:Coefficients[a] (Quartzite)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	75,156	20,921		3,592	0,016
	Young’s modulus	1,004	0,355	,785	2,829	0,037

a. Dependent Variable: UCS